CHARACTERIZATION AND SPATIAL VARIABILITY OF A PHOSPHATE MINESOIL IN CENTRAL FLORIDA

BY

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As of 1978, 20% of Polk County, Florida, was owned by phosphate mining companies. Seventy percent of that land was either being mined or had been mined. Mine lands exist predominantly in agricultural areas, so characterization of minesoils will be vital in planning for future agricultural uses. The present soil characterization system is based primarily on types of minesoil "parent materials," including overburden (spoil), sand tailings, clay, or mixes of these materials.

Initial reconnaissance of spoil indicated that conventional soil characterization techniques might not be adequate to assess differences in spoil types. Therefore, this study was designed to assess both minesoil characteristics and spatial variability of the spoil. Samples were taken from two grids and two transects, all nested. Points were spaced 50 x 200 m, 10 x 10 m and 1 m apart.

Average values of the surface 25 cm were H_2O-pH 6.6, KCl-pH 5.6, sand 83%, organic carbon (OC) 0.5%, cation exchange capacity (CEC) 10 meq/100 g, extractable K 0.096 meq/100 g, extractable Mg 2.1 meq/100 g, and extractable acidity 4.7 meq/100 g. All values except extractable K appeared to depend on position with respect to spoil islands. Average subsurface values were H_2O-pH 5.9, KCl-pH 5.6, sand 84%, OC 0.36%, CEC 9.8 meq/100 g, extractable K 0.03 meq/100 g, extractable Mg 2.4 meq/100 g, and extractable acidity 3.8 meq/100 g.

Direction-dependent and direction-independent semivariograms were calculated for each parameter. Except for elevation, all exhibited a nugget variance and sill. The nuggets of sand, CEC, OC, extractable acidity, and K were greater than 40% of the respective sill values. Organic carbon had the shortest range (90 m) and extractable K exhibited the longest (400 m).

The combination of long ranges, large nuggets, and placement of sampling grids contributed to imprecision of parameter contour mapping over the field. Kriged and non-Kriged maps of sand and OC were compared. Both types of maps were relatively inaccurate; neither map was superior to the other. Increasing the density of Kriged points from the same number of measured points does not result in more accurate contour mapping. It is recommended that a sampling scheme have relatively equal numbers of points spaced at

varying distances apart, spread evenly over the study site to maximize understanding of spatial variability.

INTRODUCTION

The soils of Polk County, Florida, were originally surveyed in the mid 1920's with the county report published in 1927. The county is currently being resurveyed because of changes that have taken place in the last 50 or so years. Most significant is the increase of knowledge about soils leading to changes in soil series. Some of the old series have since been recorrelated and renamed.

Another significant change is the amount of mine land that exists today. As of 1978, 20% of Polk Co. was owned by phosphate mining companies. Fourteen percent of Polk Co. was either being mined or already had been mined (USEPA, 1978b). The majority of the remainder of the county will probably be mined in the near future.

Since the mine land of Polk Co. is located predominantly in an agricultural area, characterization of the minesoils will be vital in planning for future agricultural uses. The mining companies are already using the land for pasture, citrus, and short rotation pulpwood plantations. Additional land could be put back into either agricultural or forest use as more land is reclaimed and sold back to private citizens.

Currently, the U.S.D.A. Soil Conservation Service (SCS) is mapping minesoils as part of the Polk County Soil Survey. The SCS system is based primarily on the types of "parent materials," including overburden (OB), sand tailings (ST), clay, or mixes of these materials in which the minesoils are developing. Two examples of minesoil map units in Polk County are Arents, which encompass the OB soils, and Psamments, which are the ST soils (personal communication, Richard Ford, Soil Survey Party Leader, USDA Soil Conservation Service, Bartow, FL, May, 1982).

Since the Psamments' variability is limited to differences in particle size and the quantity and mineralogy of phosphate and trace minerals, the mapping of this unit should be adequate. Overburden, on the other hand, is much more variable since it is a mixture of all soil and substratum materials above the mineral ore. Presence or absence of such materials as dolomite, leach zone material (upper part of the Bone Valley Formation leached of most of the Ca-phosphates), clay layers, argillic horizons, spodic horizons, or even organic matter from swamps, bayheads, or cypress domes will affect the minesoil characteristics.

Soil maps and legends that do not reflect the possible differences in minesoils developed on OB will not be very valuable to managers of that land type. After many decades of mining, the OB mine land type is very extensive in Polk County. As the acres of land reclaimed to this type are

increasing, the importance of a complete classification scheme also increases.

One objective of this study was to characterize some common chemical and physical properties of the minesoils developing in OB. The OB in an OB-capped ST setting was chosen since this setting is one of the most common types of reclaimed mine land being built today (J.D. Carson, Director of Reclamation, AGRICO, Mulberry, FL, May, 1982). To relate the properties of minesoils to native soils, standard procedures were to be used. Another major objective was to study spatial variability of soil parameters so that future data would be collected in a manner that would be more representative of the minesoil parameters in the field.

LITERATURE REVIEW

Geology

The Land Pebble Phosphate District includes seven Florida counties: Hillsborough, Polk, Hardee, Manatee, Sarasota, DeSoto, and Charlotte (Fig. 1). The Hawthorn group of geologic formations contains the principal phosphate bearing formations in this area. These formations dip gently to the south and southeast.

Miocene sediments in Florida are characterized by authigenic dolomite and phosphorite mixed with a flood of terrigenous sediments which transgressed across the peninsula as the Gulf Trough ceased to exist. The Gulf Trough separated the continental landmass and its terrigenous sediments from the Eocene-Oligocene limestone banks. The Hawthorn group is defined as the phosphatic portion of the Miocene-Pliocene sediments and has been divided into three lithologic formations: (1) Miocene Arcadia, (ii) Miocene Noralyn, and (iii) Pliocene Bone Valley Formation. The open marine Arcadia Formation consists dominantly of dolomite mixed with primary allochemical phosphorite and subordinate amounts of terrigenous sediments. The Arcadia Formation contains the vast phosphorite resources of the future. The Noralyn

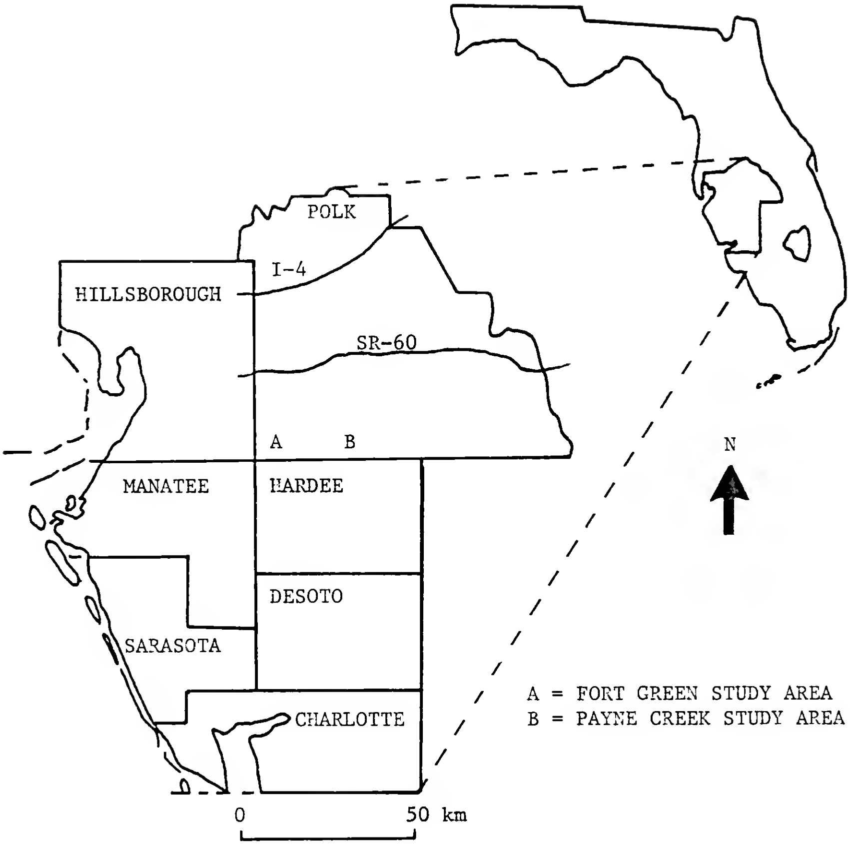


Fig. 1. Counties of the Land Pebble Phosphate District of Florida and study site locations (A and B) in southwest Polk County.

Formation consists of shallow-water, coastal-marine, terrigenous sands and clays mixed with primary orthochemical and allochemical phosphorite. The bulk of phosphorite is presently being mined from the Noralyn Formation. The Bone Valley Formation is a thin and local unit of fluvial, estuarine, and coastal-marine sediments composed of terrigenous sands and clays, abundant shell material, and reworked lithochemical phosphorite. Only locally does the Bone Valley Formation contribute a major portion of the P being mined (Riggs, 1979a).

Riggs (1979b) claimed that the formation of lithologic units with such significant amounts of P is considered abnormal. In addition, he noted that the mechanism for phosphorite formation is probably much more complicated than the simple chemical precipitation of apatites from a nutrient-rich, upwelling, current system. He noted that, in order for the phosphorite to accumulate, a shallow-water, coastal environment is essential during the time of primary phosphorite sedimentation. There must be a series of structural arches or highs providing a shoaling environment and adjacent basins and embayments. An appropriate topography must exist both to produce the phosphorite and to allow for its accumulation.

The reasons for phosphorite formation are not generally agreed upon. Riggs (1979b) reviewed the literature and brought forth two plausible reasons. He suggested that the associations of phosphate with dolomite and the Mg-rich

minerals such as montmorillonite, palygorskite, and sepiolite, and with high levels of fluorine and other trace minerals, were caused by volcanic ashfalls of significant duration. The ash would have supplied the Mg and trace elements and the P would have resulted from the decaying marine organisms poisoned by the ash.

Riggs (1979b) then introduced a more probable reason, saying that phosphorite formation appears to occur during periods of changing tectonism, leading to the supercharging (supersaturation) of the regional chemical systems of bottom waters. The cold, supercharged, almost toxic bottom waters upwell into shallow shelf environments and across the structural highs. The P accumulates as precipitates of loose, colloidal, microcrystalline mud in suspension that Riggs calls microsphorite plus biologically produced teeth, bones, shells, and mollusk kidney stones.

The orthochemical microsphorite mud plus other sediments, along with dolomite and biological particles, responds to local energy conditions and biological processes within the environment. Small animals ingest the muds, sediments, dolomites, and other micro-particles and excrete them in pellet form. In low energy environments, the muds settle, indurate, and break up producing intraclasts. Under higher energy situations, some of the mud is physically aggregated, producing oolites or pseudo-oolites. The phosphate gravels, sands, and clays are transported along and off of the shoals, diluted by sediments and chemicals

(limestone and/or dolomite), and deposited in basins where they accumulate.

A typical stratigraphic section, from a phosphate miner's viewpoint and from the surface down, consists of topsoil or surface soil, residual sand mantle called the overburden (OB), leach zone, matrix zone, bedclay zone, and bedrock zone (USEPA, 1978c).

The residual sand mantle varies from about 1.5 to 9.1 meters in thickness due to differential primary sedimentation, weathering, and reworking of materials. Sand and altered clays (kaolinite altered from montmorillonite), predominate, although montmorillonite, apatite, and vivianite are also present (Altschuler et al., 1964).

Altschuler et al. (1964) stated that the nature of the OB may be the most striking geomorphic and stratigraphic consequence of the supergene groundwater alteration. Voids in the sand are created by volume losses due to clay transformation and/or leaching, loss of the swelling property (montmorillonite), and clay translocation. The result of such clay movement is the presence of cutans lining the floors of cavities, coating fractures, and forming minor clay hardpans throughout the weathered zone.

The leach zone is part of the phosphorite which has been modified by weathering processes, varying from 0.3 to 3.3 m in thickness. Characteristically, it is vesicular, and may be friable or indurated. Quartz sand is cemented and indurated by the secondary minerals wavellite,

crandallite, and millisite. Discontinuous hardpans located between the leach zone and the matrix are composed of the various movable materials leached from above by acid ground waters and precipitated in the upper matrix zone due to the effect of ground water neutralized by basic calcium phosphates (USEPA, 1978c).

The matrix zone, ranging from 0 to 15.2 m in thickness, consists of an unconsolidated mix of phosphate pellets and granules (concentrate) and cobbles and boulders (pebbles) of phosphatized limestone, quartz, sand, silt, and clay (USEPA, 1978c). Various compositions of carbonate substituted apatite exist between the end members, fluorapatite, and hydroxyapatite. Apatites exist along with montmorillonite, quartz, chert, and calcite. Although many cations commonly substitute in the apatites, the most important one but not most abundant is uranium. It occurs in concentrations of about 0.01% (McKelvey, 1955).

A bedclay zone, the uppermost part of the Arcadia formation, is derived from the movement of clays out of the OB, leach zone, and matrix. It underlies the matrix discontinuously. It is a water-saturated, plastic sandy clay, grading into dolomite below. Usually, it has a higher uranium content than the matrix and is sometimes mined if the P_2O_5 content is economically significant. Common minerals include attapulgite, montmorillonite, quartz, and dolomite (Altschuler et al., 1964).

Below the bedclay zone is the bedrock zone, which comprises the presently noneconomic parts of the Arcadia Formation. It is composed of a fine-grained sandy and marly dolomite, and dolomitic sand and marls, all of which are sparsely phosphatic (USEPA, 1978c).

Phosphate Mining

Large scale surface mining of phosphate in the Land Pebble Phosphate District started in 1888. The value of the rock mined in 1892 had already surpassed $1 million (Wang et al., 1974). Production of phosphate rock in Florida peaked in 1980 at 43.0 million metric tons (Florida Phosphate Council, 1983), declined to 42.8 million metric tons in 1981 and to 30.0 million metric tons in 1982. This decline was due to a combination of the following factors: high interest rates, low crop prices, adequate soil P levels, increased foreign competition, and strength of the dollar (Stowasser, 1981).

In the U.S., the majority of phosphate is used for agricultural purposes, mainly as ordinary and triple superphosphate. Other uses include leavening agents, water softening and cleansing agents, plasticizers, insecticides, military smoke screens and incendiary bombs, fluorescent lights, television tubes, animal feed supplements, beverages, ceramics, catalyst and oil refining agents, photography, and dental and silicate cements (Ruhlman, 1956).

The phosphate mining industry is economically important to Florida. Each job in the phosphate industry generates 6.2 other jobs. For each dollar of income the phosphate industry generates, 3.4 dollars of other income are generated. And for each dollar of increased phosphate industry activity, 3.8 dollars are generated in other economic activity (USEPA, 1978a).

Another economically important fact is that the phosphate companies own large amounts of land. Phosphate companies own 2255 km^2 or 14.1% of the seven county Land Pebble Phosphate District. Of this land, 20% is currently being surface mined or quarried, or exists as pits. The rest of the land exists as herbaceous range land, crop or pasture land, orchards and groves, forested wetlands, and evergreen forest land. The most common land use is as herbaceous range land (USEPA, 1978b).

The most common use of land not owned by phosphate companies is range land 31.3%, followed by crop and pasture land 22.2%, wetlands 12.3%, and urban or built up land 9.3%. DeSoto and Hardee Counties have mostly agricultural land. Sarasota and Charlotte Counties have significant amounts of urban or built up land. Manatee County is built up along the coast but underdeveloped elsewhere. Hillsborough County is one half urban and one half agricultural. Polk County has the most diverse land use. The northwestern corner, north of Interstate 4, is primarily agricultural, the land between Interstate 4 and State Route

60 mostly urban or built up, and the land south of State Route 60 is split between agricultural and mine use (USEPA, 1978b) (Fig. 1).

Phosphate mining in the area, while disruptive in the short run, is not expected to affect land use drastically in the long run. Although the area occupied by mining activities is expected to rise 13.5% between 1975 and 2035, it is expected that most of the land will be returned to premining uses (i.e., mainly agriculture or range). A 7% decline is expected in agricultural land and another 7% decline in range land. These anticipated declines are not attributable to mining but to the 44% expected increase in urban or built upland (USEPA, 1978e).

Surface mining for phosphate began in the District when the deposits were first found. As draglines became more efficient and more rugged, ore could be extracted from beneath deeper and deeper OB.

Currently, electric-powered, walking draglines with bucket capacities of 27 to 38 m^3 and boom lengths of 69 to 84 m are used to mine phosphate. The land is cleared of trees and brush, swamps are drained and muck or peat is removed in preparation for the start of mining. The dragline "walks" adjacent and parallel to the mining face in increments of about 23 to 38 m, moving the OB and extracting the ore. This procedure is repeated for a distance of 0.1 to 1.6 km before the dragline moves away from the mining

face and starts its walk back, creating a new mining face as it goes (USEPA, 1978d).

The matrix is dumped by the dragline into a pit, slurried, and hydraulically pumped to the beneficiation plant. Beneficiation encompasses the processes involved in separating economically valuable phosphate from the inert sand and the clay slimes which are part of the matrix. The processes include washing, milling (hammermill), screening, clarifying, separating, and floating.

In the first step, the coarse phosphate rock is separated from clay, sand, and fine phosphate via washing, screening, and milling. The product is rock phosphate having particle diameters between 1.5 and 19 mm. Material smaller than 1.5 mm is washed again, removing waste clay slimes consisting of particles smaller than 0.1 mm. The remaining material is now ready for the flotation processes. One process is for materials greater than 0.5 mm in size and the other process is for materials less than 0.5 mm. During these processes, sand tailings (ST) and more clay slimes are removed. Since the whole sequence of processes involves the use of large quantities of water, the waste products are pumped to disposal areas as they are removed from the ore (USEPA, 1978d).

The OB (sometimes called spoil after mining) is a mix of topsoil, subsoil, and all substrata including leach zone materials, above the matrix. The OB remains at the mining site, piled in long parallel rows 46 to 76 m apart. This

pattern results from the geometry of the dragline's boom length and the arc through which the dragline swings. After mining is complete, groundwater pumping stops and the water table rises, causing long lakes to form between spoil rows.

Reclamation of these mined landscapes can be accomplished in several ways. The simplest method is simply to grade the spoil rows, forming shorelines around the finger-like lakes. Other methods involve filling of the valleys between the spoil rows with beneficiation waste products. Sand or a mix of sand and clay can be used as fill, raising the average level of the land. The spoil "islands" that remain are flattened and spread out over the other materials. The mining can also be planned so that the spoil rows act as dikes and the whole area may be turned into a clay settling pond. Once the clays have dried sufficiently, the area can be capped with sand or OB to improve stability, though not to the point where construction is feasible.

Revegetation of mined lands to forage species has been the primary practice in the District because forage types can be chosen to match the different spoil characteristics and because quick growing grasses hinder erosion. Reforestation and row cropping of these areas have been minimal. Although Wright (1980) states that citrus has done poorly on mine sites due to the infertile and droughty nature of the spoils, the real cause of poor growth may be lack of proper management (personal communication, Don Morrow, General

Manager, Mining Operations, AGRICO, Mulberry, Fl, May, 1982). After several reclamation failures, AGRICO now realizes that they must first become acquainted with and then follow prescribed management procedures for any new reclamation endeavor such as citrus.

Detailed information on the characteristics of the three types of materials resulting from mining and beneficiation of phosphate rock is limited. General information is common. Sand tailings have low water holding capacity, little organic matter, and minimal fertility (Mislevy and Blue, 1981; Hawkins, 1983). Properties of ST resemble properties of soils commonly underlying sand pine-scrub plant communities (EcoImpact, 1981).

Dried phosphatic clay materials range in clay content from 27 to 83%. Although they have excellent nutrient and moisture retention properties, they are prone to water-logging and thus very difficult to cultivate (Hawkins, 1983).

Hawkins (1983) stated that spoil typically has better natural fertility and better moisture holding capacity than native soils due to slightly higher contents of clay, Ca, Mg, and K. He noted that because of the higher clay content, particularly when organic matter was absent, the spoils became very hard and cloddy when dry and very plastic and slick when wet. Phosphatic clay soils have excellent nutrient and moisture retention properties but are also very difficult to cultivate and prone to waterlogging. Sand

tailing soils, on the other hand, have very low nutrient and moisture retention properties but are easy to cultivate. Hawkins based his descriptions of the three types of minesoils on particle size determination, pH, Ca, Mg, P, and K analyses for 12 samples from reclaimed mine lands 5 to 50 years old.

The land areas of spoil, ST, and clay from phosphate mining activities are of sufficient size to be routinely delineated by the Soil Conservation Service (SCS). The SCS is currently conducting a soil survey in Polk County. Soil map units being used for the minesoils include three materials alone and in combination. Spoils are called "Arents" in the Polk County soil survey legend; ST soils are called "Psamments"; clay soils are called "Slickens" if still watery and "Slickens, dewatered," if dry. An example of a map unit name given to a combination of materials is "Arents, clayey substratum," which describes spoil capping dried clay on an old clay settling pond (personal communication, Richard Ford, Soil Survey Party Leader, USDA Soil Conservation Service, Bartow, FL, May, 1982).

Some of the insights gained in coal mine reclamation research can be useful in interpreting data trends in phosphate mine research. Coal mine reclamation research was started earlier than phosphate mine research, possibly because the problems are much more visible in and around a coal surface mine on the side of a hill than in a phosphate mine in relatively flat terrain. Acid mine drainage

devastated entire watersheds, turning all the stream beds a bright orange color while highwalls and lines of deforestation ringed the mountains. Recent research has moved away from looking at revegetation problems and has instead emphasized the chemical, physical and microbiological properties of the minesoils, applicable analytical procedures, variability of minesoil properties, and the comparison of minesoil properties with native soil properties.

Ciolkosz et al. (1983) studied 25 minesoil pedons located predominantly in Western Pennsylvania. They found the minesoils to be deep and well drained, and to have subsoil rock fragment contents of >70%. Surface or near surface horizons had from 40-60% rock fragments and predominantly medium textures (loam, silt loam, clay loam). High rock fragment content made these soils droughty and reduced their effective cation exchange capacity (CEC) to a low level. Three-fourths of the minesoils had very low to low pH values. Many had salt contents at a level which restricted plant growth.

Plass and Capp (1974) found that in general coal mine spoil was deficient in nutrients, had an unfavorable moisture regime, was acid, and contained excessive salts or toxic substances. Pedersen et al. (1980) found that minesoils normally held less water at comparable tensions than native soil.

Berg (1978) noted that some sampling procedures and soil tests have rather severe limitations when applied to minesoils, especially because some users may be unaware of those limitations or give little consideration to them. Berg reviewed sampling, sample preparation, pH, lime requirement, soluble salts, Na adsorption ratio, N, P, and trace element analysis.

A more rigorous, but slightly different approach to sampling was undertaken in coal mine areas by Sobek et al. (1978). They emphasized pre-mining OB analysis in addition to sampling of minesoils. They explored what they considered to be all the important field and laboratory methods in a step-by-step fashion. They recommended characterization of OB rock strata before mining begins, so that mining and reclamation could be planned to segregate the different materials and selectively place the neutral, easily weatherable OB materials near the rooting zone and bury the potentially toxic (acid) materials beneath the rooting zone.

Apparently, the large quantities of minesoil characteristic data plus the increasing acreage of mine lands influenced the creation of a minesoil classification scheme. With 121,500 ha of highly disturbed land in West Virginia, the National Cooperative Soil Survey recognized a need for more meaningful mapping units. They provisionally approved a system for classifying minesoils developed in West Virginia (J.C. Sencindiver, 1976. Ph.D. dissertation,

West Virginia University, Morgantown, WV, as cited by Smith and Sobek, 1978).

The minesoil mapping units were based on rock types, coarse fragments (presence of splintery edges and disorder in direction of long axis), texture, pH at 25 cm in the profile, and dominant profile mineralogy. Smith and Sobek also set standards for minesoil suitability classes: (i) suitable for multiple uses; (ii) suitable for rural, urban, recreational, or industrial building sites and grounds; (iii) suitable for extensive recreation and access (hiking, camping, hunting, etc.); (iv) suitable for production of forest products; (v) suitable for pasture, hay, or other crops not requiring plowing; and (vi) suitable for intensive agriculture.

Although Ciolkosz et al. (1983) characterized 25 minesoils, they did not use the mapping units developed by Sencindiver. Instead, they used the term Minesoil and modified it with texture classes or classes based on the amount of coarse fragments.

Indorante and Jansen (1981), working on soil surface mines in the Midwest, stated that variation of some native soil properties such as bulk density, pH, organic carbon, cation exchange capacity, and particle size distribution were similar to the variation of the properties in a minesoil. Schafer (1979) studied native and minesoils in Montana, finding that native soils were less variable than minesoils on a local scale (0 to 10 m spacing) but much more

variable on a landscape scale (greater than 500 m spacing). Unlike minesoils, variation of natural soils was highly correlated with landscape features and soil forming processes at the larger scale.

Soil Classification and Variability

Soil systematics, whether natural or artificial, is largely a matter of matching like specimens, profiles, or sites, and distinguishing among unlike ones (Webster, 1975). Webster said that the main concern of the users of a classification system is that variance or a similar measure of diversity is, on the average, smaller among members of a class than among members of different classes.

The general purpose classification of soils is based on easily observable and, therefore, mainly morphological attributes (Webster and Butler, 1976). Perhaps the most widespread use of soil classification schemes is for soil survey and mapping. The soil surveyor's classes are usually defined for a few distinguishable properties that are also manageable by the users in the hope that variation in other properties is similarly restricted (Webster and Butler, 1976). In order to choose appropriate soil characteristics to use in the classification scheme, surveyors must consider the needs of the users. These needs may include information such as pH, available nutrients, and soil-water characteristics for agronomic interests, and shear strength, plastic limits, and expansion coefficients for engineering interests. It is, however, impossible to satisfy the needs

of all users because groupings of some particular soil characteristics are incompatible with the classification scheme. That is, variability of some soil attributes is larger within classes than between classes.

Even if the classification scheme is adequately based on the properties manageable by interested users, it is still useless if the graphical representation of soils information does not represent accurately the characteristics of the soils in the field. The soil survey map is the graphical representation with corresponding descriptions of observations and measurements from pits and boreholes. Even though the observations and measurements are point samples, it is hoped that mapped soil classes have values similar to the observations and measurements but different from those of other classes (Burgess and Webster, 1980). Burgess and Webster noted that the distribution of properties is displayed by assigning the typical value of that property within its class to individual parcels on the map. The majority of values are assigned to areas that have not been sampled, so these values instead must be predicted. The predicted values may be different from the actual values.

The validity of soil survey maps depends on the accuracy and precision with which the samples represent the characteristics of soils in the field. Studies of soil variability show that accuracy and precision of soil mapping are not perfect (Reynolds, 1975; Campbell, 1977, 1978;

Mausbach et al., 1980; Lanyon and Hall, 1981; Russo and Bresler, 1981a, 1981b; Sisson and Wierenga, 1981; Edmonds et al., 1982; Lascano and Bavel, 1982; Cassel, 1983).

Proper soil sampling techniques are paramount to determining variability of soil properties. Cline (1944) stated that sampling error was commonly much greater than analytical error. He said that the accuracy of chemical analysis in defining field soil characteristics depends on the degree to which (i) the gross sample accurately represents the soil from which it was taken, (ii) no changes affecting the results occur in the sample prior to analysis, (iii) the subsample analyzed accurately represents the gross sample, and (iv) the analysis determines the true value of the character under test. Precision is increased if several small samples from the whole are used rather than one larger one. Also, since a sample represents values over some limited area, precision is maintained if the sampling scheme stays within the areal limits (Cline, 1944).

Reynolds (Ph.D. Dissertation, University of Bristol, as cited by Reynolds, 1975) studied variability of soils along slopes and found that increasing the number of samples to reach a desired level of precision is not always feasible. To estimate the mean of pH, soil depth, soil-water, and organic matter populations with 1% precision would require as many as 689 samples. If a precision of 0.2% were chosen, as many as 17,227 samples would have to be taken.

Considering the number of samples Reynolds found necessary for precise soil sampling, it is not surprising that most often the number of samples taken to characterize a soil series is found to be inadequate (Ike and Clutter, 1968).

Reynolds' findings were based on his idea of how soil variability should or could be studied. More variable soils required more samples to reach a given precision than less variable soils. This type of research has limited value in solving problems associated with validity of soil maps. In studying variability of forest soils, Ike and Clutter (1968) found that even though estimates of population mean values were accurate, the sample provided little information as to the nature and pattern of variability of the properties measured.

Instead of doing research that would help to reduce variability of soil property measurements, workers have begun to study the variability itself. Edmonds et al. (1982) studied short-range and long-range variability in soils. They found that extreme short-range variability within delineations of natural landscape elements or pedons caused long-range variations to seem erratic. Mausbach et al. (1980) studied the variability of measured properties in morphologically matched pedons and found that a transect sampling scheme is practical in assessing trends in areal distribution of a property. Campbell (1977, 1978) studied variability of soil properties across soil boundaries. He defined three variability models: (i) completely random

values with no coherent pattern to their distribution, (ii) gradual variation of measurements without distinct boundaries (i.e., the contact between two soil types can be represented by a trend surface), and (iii) distinct, uniform soil regions separated by abrupt boundaries such as are implied by soil maps. He also suggested that other workers' problems with sampling studies were caused by failure to consider sample spacing or arrangement.

Geostatistics

In the 1970's, soil scientists began using geostatistics to study the variability associated with spacing and geometry of sample points. Geostatistics, or statistical methods applied to geological ore reserve estimation, evolved with the need for increased precision of estimating quality or quantity of ore. In an ore reserve evaluation, homogeneous regions are determined and values are assigned on the basis of judgement and fact (Popoff, 1966). The facts are determined from exploratory data, spot sampling, production data, or data from other parts of the same deposit.

In addition to geostatistics, some of the methods used to predict areal values from point sample values include (i) method of isolines, (ii) method of triangles, (iii) method of polygons, and (iv) distance weighting.

Rutledge (1976) listed three fundamental objections to these conventional methods:

(i) The procedures for assigning values (to "chunks" of ore body) are arbitrary and without a sound theoretical basis; the methods are a function of geometry of samples rather than a function of the quality of the ore.

(ii) The procedures can be biased and there is no way of ensuring against bias.

(iii) Estimation procedures either do not include a method of determining the precision of the estimate, or allow precision to be determined inaccurately.

In addition to the above, two more objections are given to the use of distance weighting methods. First, Rutledge (1976) said that using arbitrary distance functions "merely formalizes the mystical principle of gradual change" (1976, p. 300). Second, this method assumes that samples are random, which may not be the case. Criticism of these procedures has also been put forth by Delfiner and Delhomme (1975), Clark (1979a), Royle (1979), and Burgess and Webster (1980).

Royle (1979) tempered his criticism by admitting that sometimes the above methods are accurate estimators. He noted that variance of a population is made up of both a random component and a spatial component. The methods work well when the random component is small due to the smaller chance of choosing a sample whose value is far from the mean. As the random component increases relative to the

spatial component, the methods become less and less useful. Like Royle, Delfiner and Delhomme (1975) stated that the procedures were optimum only in limited situations. Their main objection was that the procedures could not be used to filter the random factor from the sample interrelationships. The estimated surface would still pass through the sample points even if highly erratic, giving an unrealistic map.

Krige (1976) stated that when he first tried to estimate gold ore reserves, he found it impossible using common statistical methods. He said that without mathematical statistics or geostatistics it was impossible to find an underlying logical pattern. He studied the pattern of distribution of 300,000 values from 24 gold mines, including gold, uranium, and pyrite contents. His approach was not based on any theories but on practical observations and experimentation.

In writing about the history of geostatistics, Krige (1976) stated that Matheron is responsible for the development of "Regionalized Variable Theory" (RVT) and the use of semi-variograms. Royle defined regionalized variables as, "those variables whose values are related in some way to their positions" (1979, p. 92). Huijbregts (1975) noted that, even though the variables seemed unpredictable and highly erratic, their behavior is not completely random. He said that neighboring points are related by a complex set of correlations which he called the

"structure." In order to analyze properly any spatial phenomena, one ". . . must be able to extract from the apparent disorder of available data the major structural characteristics of the phenomena and a measure of the correlation between values at neighboring points throughout space" (Huijbregts, 1975, p. 38).

Semi-Variograms

Huijbregts (1975) described a variogram, $2\gamma(h)$, as the average quadratic deviation between values, (Y), at two points, x and $x+h$, of space:

$$2\gamma(h) = E([Y(x+h) - Y(x)]^2) \quad . \tag{1}$$

Commonly, $\gamma(h)$, the half- or semi-variogram, is used. The interval, h, or the lag, has direction and therefore is a vector.

In order to use Eq. (1), it is assumed that the distribution of the differences in values between the pairs of points is the same over the area of interest (i.e., "quasi-stationarity" exists) (Clark, 1979a). In other words, $\gamma(h)$ does not depend on the magnitude of the x values or on the domain (area) where $\gamma(h)$ is estimated.

The semi-variogram is the minimum structural tool and the minimum statistical tool needed to make a structural analysis. Another way of wording Equation 1 is that $\gamma(h)$ is the variance of the error made when estimating $Y(x+h)$ by $Y(x)$, and thus reflects the ability of $\gamma(h)$ to solve any estimation problem. Since the function $\gamma(h)$ has properties

closely associated with the structural features of the population, it can be used to quantify those features. The basis of structural analysis is the study of the behavior of the semi-variogram with respect to values and direction of the vector (h) (Huijbregts, 1975).

The equation used in calculating a semi-variogram is

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Y(x_i+h) - Y(x_i)]^2 \qquad (2)$$

where $\gamma^*(h)$ is the calculated semi-variogram,

$N(h)$ is the number of pairs of points used in the calculation,

Y's represent the measured values in space separated by a distance (scalar) along the vector h.

As the histogram is to the population distribution function, $[\gamma^*(h)]$ is to $[\gamma(h)]$. The estimate $[\gamma^*(h)]$ of the true semi-variogram generally increases as h increases, and it is the pattern of this increase that is used in determination of structure.

In practice, points are plotted on a graph and a mathematical model is fit to them. Five models are most commonly used (Gambolati and Volpi, 1979): (i) spherical, (ii) exponential, and (iii) Gaussian, for curves that tend to level out (have a sill) with increasing h, and (iv) linear, parabolic, or root, and (v) logarithmic, for curves that do not have a sill (Fig. 2). In these models, c is the "nugget," the Y intercept (except for the logarithmic model

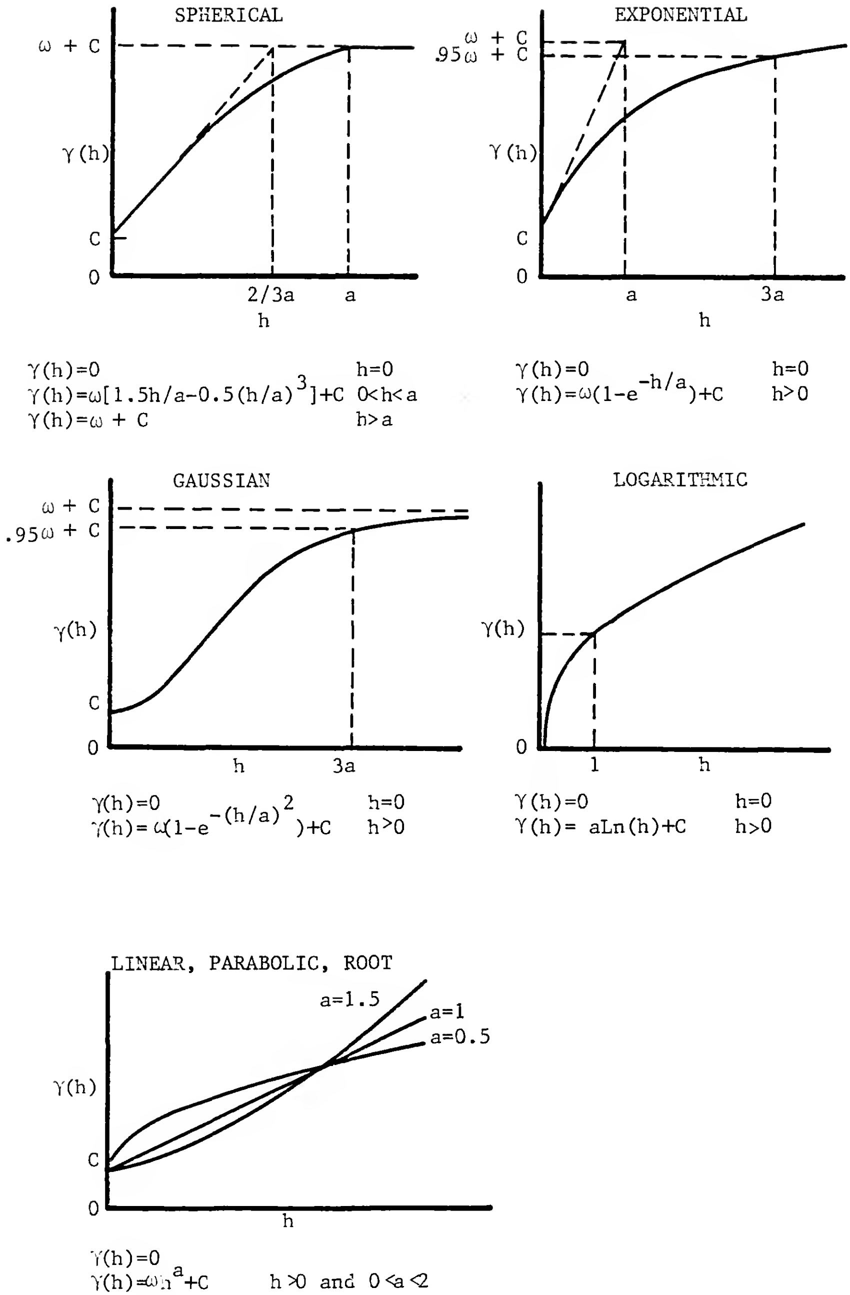
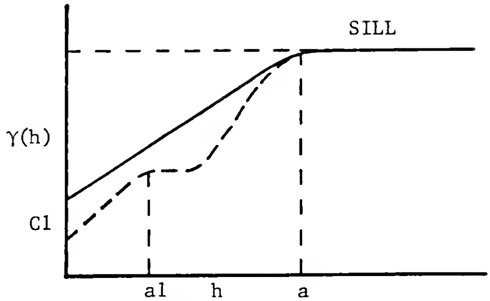


Fig. 2. Most commonly used theoretical semi-variograms.

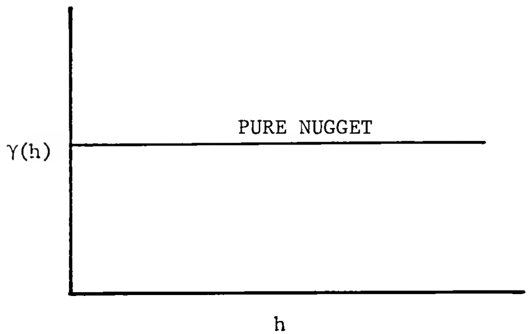
where C is the intercept of X=1); a is the range, the value along h where the semi-variogram levels out; the sill is the $\gamma(h)$ value where the curve levels off; and ω is the difference between the sill and nugget values. Not every mathematical model can be used because, by theory, the models must be conditionally positive definite (always giving a positive value).

A few characteristics of the semi-variogram give immediate information to the user (Fig. 3). Theoretically, the Y intercept would always be zero. The value at one location should equal the value of another sample taken zero distance away. When the Y intercept is greater than zero, the semi-variogram has a "nugget," indicating that at least a part of the variability is random or that the sampling scheme was too coarse to eliminate all of the positional variability. If the intercept is such that the semi-variogram is flat, then the sample positions were too far apart to see any correlation, and variability is completely random (Fig. 3, Situation A).

The value (a) along h, where the semi-variogram levels out, is called the range or zone of influence. Pairs of points closer together than this distance are in some way correlated. Members of pairs farther apart are independent from each other. The value of $\gamma(h)$ at which the semi-variogram levels out is called the sill. This value approximates the variance of the population.



SITUATION A



SITUATION B

Fig. 3. Schematic diagram of typical semi-variogram curves; Situation A exhibits nesting, Situation B pure nugget.

If the calculated semi-variogram increases at least as rapidly as $(h)^2$ for large distances of h (parabolic shape), then a trend is indicated. This condition may also be expressed as regional drift (Journel and Huijbregts, 1978). Local drift is exhibited by a periodic rise and fall in the semi-variogram (Clark, 1979b).

If the semi-variogram starts at c1 along Y (Fig. 3, situation a) then two ranges exist, a1 and a, and the semi-variogram is said to exhibit nesting (Huijbregts, 1975). A semi-variogram is additive for all ranges and sills that may be present. If a subordinate range and sill are significant then they may show up in the curve as extra inflection point(s).

Another structural feature can be seen by viewing several semi-variograms from the same population. Because h from the semi-variogram equation is a vector, it is important to calculate semi-variograms in different directions. If the resulting semi-variograms have different ranges or sills, the material (soil) is anisotropic. That is, the spatial correlation among points changes with direction. The direction-independent semi-variogram might exhibit "nesting" or inflections when its component semi-variograms are different from each other.

Kriging

An estimation procedure, called Kriging, is used to estimate values optimally at unsampled locations. The general equation is

$$\hat{Z}_o = \lambda_1 z(x_1, y_1) + \lambda_2 z(x_2, y_2) + \ldots + \lambda_n z(x_n, y_n) \qquad (3)$$

where $\hat{Z}_o$ = the linear sum or weighted average of parameter Z at location (x_o, y_o),

$Z(x_n, y_n)$ = measured values of parameter Z at locations (x_n, y_n),

λ_n = coefficients or weights associated with the data points.

This is the same type of equation used for other distance-weighting estimators except that, in Kriging, the weights are chosen so that error associated with the estimate is less than that for any other linear sum. The λ's depend on the known spatial dependences as expressed by the semi-variogram and the geometric relationships among the observed points (distances between measured points and the point to be estimated). Kriging is an unbiased estimator, meaning that the average error of its estimates is zero. Whenever the sample population is normally distributed, Kriging is the Best (estimation variance is a minimum) Linear (uses linear combinations of equations based on neighbor point values) Unbiased (the average error of its estimates is zero) Estimator (BLUE). Rendu (1978) stated that in practice, the assumption of a normal distribution of the sample values is not often satisfied except when the sample mineralization (ore body) has a relatively high grade or when the value considered has a low variability. He further stated that judgement and past experience would then be used to decide whether the assumption of normality could be

used. This latter statement results in much discomfort for beginning geostatisticians.

Additional discomfort is generated by the number of Kriging variants or alternatives that exist to overcome the effects of non-normality or non-stationarity. Some of the variants will be discussed below.

Punctual Kriging is simply estimation of point values resulting in the most accurate isarithmic map that can be made using a normally distributed set of point data. Sometimes however, local discontinuity can obscure long range trends in the maps. Block Kriging, the Kriging of areas rather than points can be used to overcome this problem resulting in smaller estimation variances and a smoother map (Burgess and Webster, 1980b). Universal Kriging was designed to overcome the effects of non-stationarity. In this variant, the trend is mathematically removed from the data before calculating the semi-variograms. The requested number of points are Kriged and then the trend is added back into the Kriged points. Sometimes universal Kriging is also capable of transforming a non-normal population into a normal population during trend removal.

Two Kriging variants, lognormal and disjunctive Kriging, were designed to overcome the problems due to non-normal data. Lognormal Kriging, as the name implies, is used when data are positively skewed. The semi-variograms are calculated on the logtransformed data. Disjunctive

Kriging is used when any other best-fit transform is used to convert data into a form that approximates a univariate normal distribution. The semi-variograms are calculated on the transformed data (Henley, 1981).

Henley (1981) found fault with the Kriging variants that attempt to overcome problems of non-normality or non-stationarity. He found that most authors of geostatistics suggested that departures from stationarity were not of practical significance since local stationarity was often assumed. Henley stated that no general proof or statistical test existed to determine whether such an assumption was warranted.

Henley (1981) also objected to the use of lognormal and disjunctive Kriging. The variable to be estimated (after transformation) is a non-linear function of the original data. This function may, in fact, be very complicated. Henley stated that these methods produced a sub-optimal, non-linear, biased estimator.

Krige developed the practical use of geostatistics for gold reserve estimation (Krige, 1976). Since then his system has been used widely for the study of many types of ore deposits. Journel and Huijbregts (1978) used 24 different types of deposits as examples in their book alone. Outside of mining interests, Kriging has been used to study hydraulic head of aquifers under the Venetian lagoon (Gambolati and Volpi, 1979), meteorology, pluviometry, topography (Journel and Huijbregts, 1978), and

also to study hydrogen ion concentration in bulk precipitation (Bilonick, 1983).

In soil science, Kriging and structure determination have been used to study spatial variability of various chemical and physical parameters. Campbell (1978) studied the variability of sand content and pH on adjacent mapping units. Two grids, 200 x 80 m in size, were positioned as close to each other as possible without crossing the map unit boundary. Samples were taken at 10 m intervals. Mean pH was the same for both mapping units, while sand content was 8.5% on one (Pawnee) and 1.2% on the other (Ladysmith). The 10 m intervals were not sufficiently close to show any spatial correlation for pH (i.e., a pure nugget effect was observed). Sand contents were correlated to 30 m for the Ladysmith, but the grid on Pawnee was not large enough for accurate estimation of sand (i.e., no range was found).

Vauclin et al. (1983) studied variability of sand content and available water content. They used a 10 m spacing with a grid measuring 70 x 40 m. They found that available water content values were correlated up to a 40 m range and that sand contents were correlated to 33.5 m.

Byers and Stevens (1983) studied the spatial variability of hydraulic conductivity (K) and particle size of an untilled fluvial sand. They used two 14.85 m horizontal transects perpendicular to each other and one vertical transect 4.9 m long. They used a sample spacing of

15 cm in the horizontal plane and 7 cm in the vertical plane so that the variability of the small bedding structure would not be lost. Particle size values were correlated to only 83 cm and ln K values were correlated to 60 cm.

The smaller range associated with particle size reported by Byers and Stevens (1983), relative to that of Campbell (1978) and Vauclin et al. (1983), may be a function of the sample spacing. Gajem et al. (1981) used four transects sampled at 20 cm intervals, four at 200 cm, and one at 2000 cm, to study the spatial variability of water contents, pH, exchangeable cations, surface area, mean diameter, and bulk density. Except for two cases, the range of each variable increased with increasing sample spacing. Exchangeable cation values were correlated to 1.15 m as determined by the transects with the 20 cm spacing. On the transects with 200 and 2000 cm spacings, the range was 20 m. Bulk density values were correlated to 2 m as measured on the 20 cm and 200 cm spacing transects. Gajem et al. explained the increasing range values as a function of the larger population variance encountered with larger sample spacings.

Yost et al. (1982a) used extremely large sample spacing (1-2 km) along transects to study the variability of several parameters including pH, exchangeable Ca, Mg, K and Na, and the sum of the ions. With this large spacing, they found very large ranges, 8 to 58 km. From the results, they suggested that soils over large areas may be grouped in

order to obtain uniform regions of soil properties suitable for management regimes.

In a subsequent paper, Yost et al. (1982b) used the semi-variograms to study precision of contour mapping. They found that the maps of error associated with Kriged values could be used to indicate where additional samples should be taken to provide the most information. They also found that it may not be necessary to include the trends in Kriging equations or to remove the trend in the data prior to analysis. Russo and Bresler (1982) found that adding additional points to the field at locations where maximum Kriging errors were calculated lowers the overall error more than if the points were added randomly.

Burgess and Webster (1980) studied variability of Na contents and thickness of cover loam (depth to sand and gravel) in different fields. A square grid containing 440 observations, 15.2 m apart was used for the Na study and a spacing of 20 m in another field was used to study thickness of cover loam (depth to sand and gravel). The Na semi-variogram increased linearly (no range) while the cover loam semi-variogram had a range of 101 m.

Vieira et al. (1981) studied variability of infiltration rates in a cropped field using a 55 x 159 m grid. Samples were spaced at 5 m intervals along X, skipping the rows potentially affected by crop roots. Spacing along Y was 1 m. They found infiltration measurements were correlated to 35 m. They also found that the normal distribution

should not lead to the conclusion that locations for field observations should be selected randomly. The presence or lack of spatial structure of a set of observations has no bearing on the frequency distribution of that same set. The two properties exist independently of each other.

Geostatistics is in its adolescence as a tool soil scientists use to attempt to understand variability of soil characteristics. Geostatistics has been used to study the variability of a number of soil chemical and physical properties, in fields and across regions. As the number of studies of different soil properties increases, soil scientists will be better able to compare their results with others. Jury (1984) reviewed eight studies and found a correlation between lag spacing and range. Jury called this condition a measurement bias. Other measurement biases may be found as the experience of the soil geostatisticians increases.

One of the important aspects of soil survey is knowing where to draw boundaries separating unlike soils. Soil surveyors may not be able to use geostatistics on a site by site basis but they may be able to use geostatistics to identify the spatial behavior of soils in areas of transition between soil types. Understanding the spatial structure of soils in these kinds of areas may alleviate some problems in positioning boundaries.

MATERIALS AND METHODS

Site Selection

Several "overburden-capped sand tailings" sites were chosen from AGRICO's mined-land inventory as possible study sites, with the help of J.D. Carson (Director of Reclamation AGRICO, Mulberry, FL, May, 1982). Carson stated that this land type is significant because of the large acreage either already reclaimed or yet to be reclaimed in this manner. Characterization data for phosphate minesoils were not available, so several reconnaissance surveys were made to gain a preliminary understanding of soil properties occurring in this land type.

The first profile examined was of overburden-capped sand tailings, reclaimed to pasture. It was located in southwest Polk County (Fig. 1, Location A), Fort Green area, S20, T32S, R23E (Tallahassee Meridian). This profile was described by noting distinct horizontal layering, presence of lenses, and colors, including mottles.

Profiles of spoil that had not been remixed after being deposited initially by the dragline were examined next. The profiles were in an erosion gully that cut through the spoil. This site (Fig. 1, Location B), in the Payne Creek area, located 13 Km east of the previous site, in S15,

T32S, R24E, had been minimally reclaimed to pasture in a land-and-lakes topography. The tops of the spoil piles were leveled, forming long (approx. 500 m), narrow (approx. 50-150 m) strips of level land between similarly sized and shaped lakes.

Profiles 1 and 2, located nearer to the head of the gully (Fig. 4), exhibited multiple layers of various thicknesses dipping towards the adjacent lake. Profile 3, located closer to the lake in a tributary gully, was positioned perpendicular to 1 and 2 and was much more like the profile at the first site.

The layers in profiles 1 and 2 were described at two places in the profile (opposite sides of the 1 m wide face) to account for the significant dip in the layers. Since profile 3 did not exhibit such distinctive layers, it could not be described the same way. There were no distinctive features that could be measured by depth. The whole profile was described as if it were one layer by noting presence and field textures of lenses, texture of the soil matrix, and colors, including mottles.

A nearby site reclaimed to pasture in 1980 was chosen as the primary study site because it was accessible, relatively level, and high enough above the surrounding landscape to remain dry during the rainy season. It is located in the next section south of the gully site, S22, T32S, R24E (Fig. 1, Location B), in a field about 1 km east-west and about 0.75 km north-south. The western boundary of

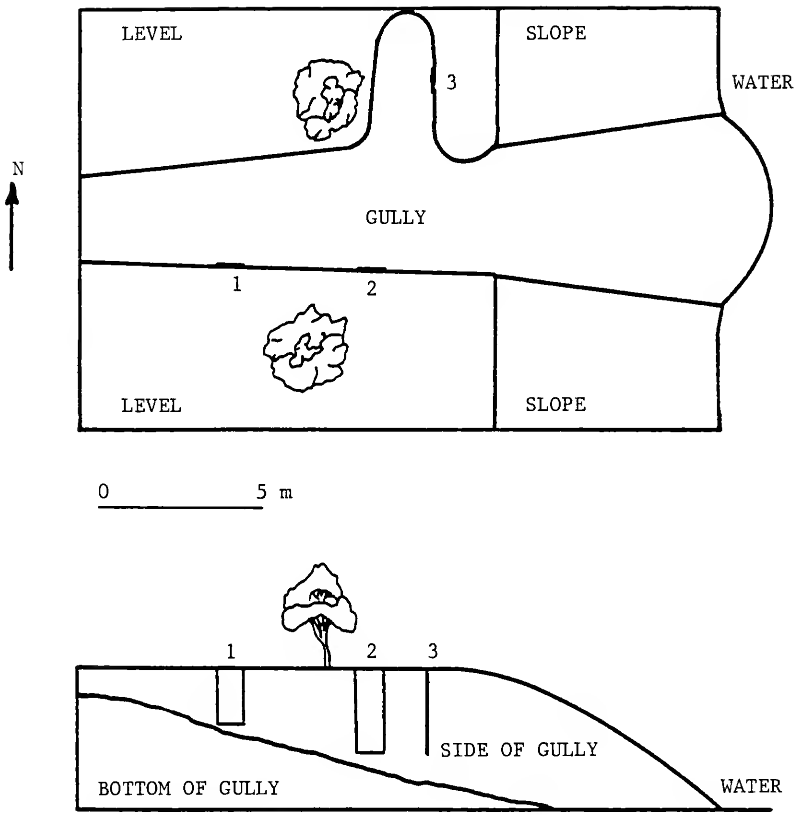


Fig. 4. Schematic of profile locations at the Payne Creek area site.

the study site was the western section line; the southern boundary was an east-west road 380 m north of the southern section line (Fig. 5). Topography was generally smooth, with minor local undulations. The highest part of the field was just northeast of the middle of the site. From here, the land sloped slightly to the eastern edge to a swampy swale and slightly to the west. To the south, it sloped sightly, then more steeply (5% slope) leaving about 150 m of level land adjacent to the road. A small creek drained the swale running through this low section and under the road. The steepest part of the south-facing slope paralleled the road from the swale on the eastern side to an area about 400 m to the west, where it then curved north. From this point, it became less steep and separated into several terraces (rough berms about 1 m high installed for erosion control) spaced about 50 m apart which continued curving towards the northwest corner.

Original revegetation plans consisted of planting Bahiagrass (Paspalum notatum) and Bermudagrass (Cynodon dactylon). Hairy Indigo (Indigofera hirsuta) and Aeschynomene (Aeschynomene americana) have naturally invaded, forming a few very dense patches interspersed in the grass.

The dark, organic-rich layers apparent in these mine-soils came from the native soil profiles or wetland sediments. On the other hand, the clay and sandy clay layers probably came largely from the clay layers above the matrix

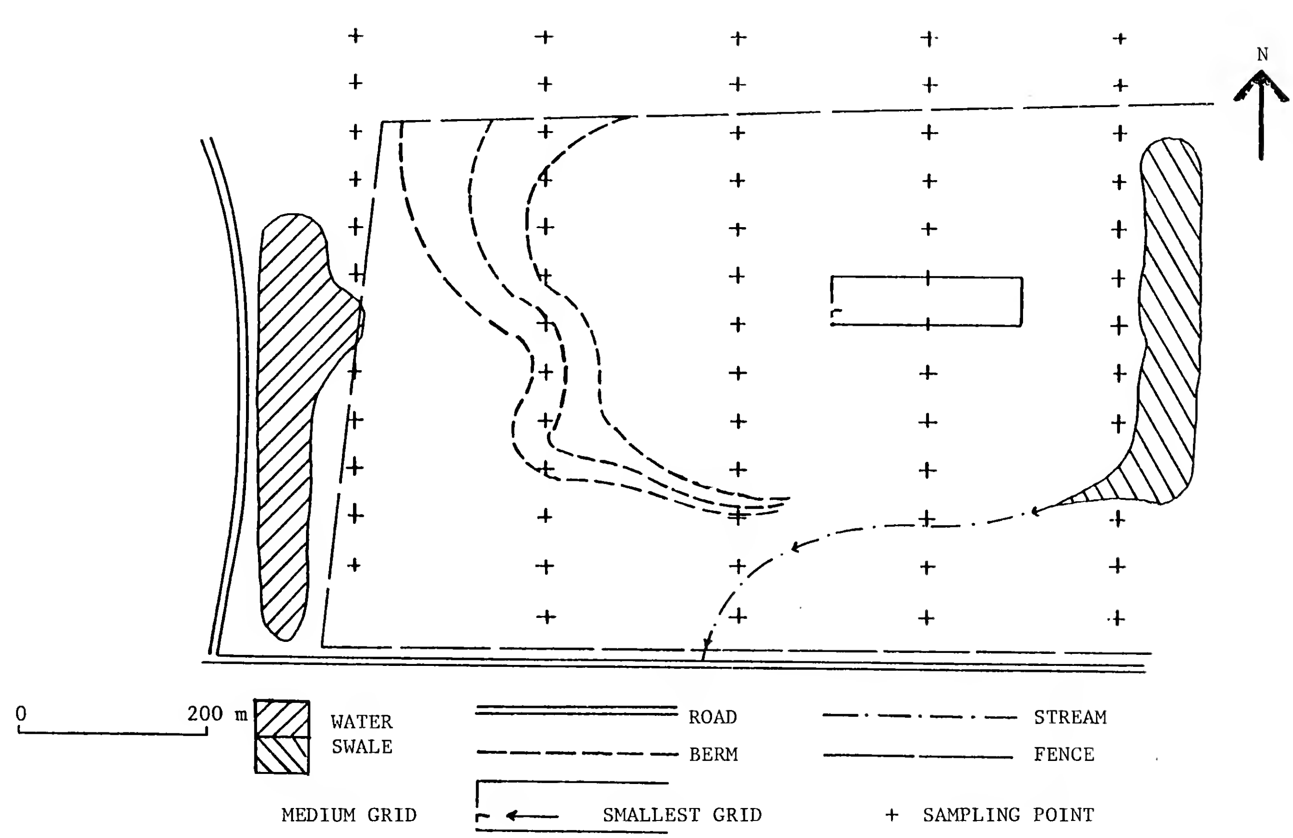


Fig. 5. Schematic showing locations of three nested grids covering the field.

and to a lesser degree from the non-extensive, loamy argillic horizons of the native soils.

Native soils on this site were all poorly drained. Another characteristic of all the soils except one (Felda) was the presence of an organic-rich horizon in the form of a spodic horizon or a mollic, umbric, or histic epipedon. The soils on the site were first described (Fig. 6) (Soil Survey Staff, 1927) as Leon fine sand (comprising 50% of the area), Leon fine sand, loamy phase (5%), Portsmouth fine sand (20%), Portsmouth fine sand, swamp phase (10%), St. Johns fine sand (10%), and Blanton fine sand (5%) (Fig. 6). Since the original soil survey, some of the soils have been re-correlated and re-named. The St. Johns fine sand has retained its name and is in the sandy, siliceous, hyperthermic, Typic Haplaquods family (Soil Survey Staff, 1975). The Leon fine sand is now called Myakka fine sand, a sandy, siliceous, hyperthermic, Aeric Haplaquod. The Portsmouth fine sand, swamp phase is now called Felda, a loamy, siliceous, hyperthermic, Arenic Ochraqualf. The Blanton fine sand is now called Tavares fine sand, a hyperthermic, uncoated Typic Quartzipsamment. The Portsmouth fine sand was split into two series, Floridana and Placid, depending in part on the texture. The Floridana contains enough clay to be loamy and is classified as a loamy, siliceous, hyperthermic, Arenic Argiaquoll. Placid fine sand, with less clay is a sandy, siliceous, hyperthermic, Typic Humaquept. The Leon fine sand, loamy

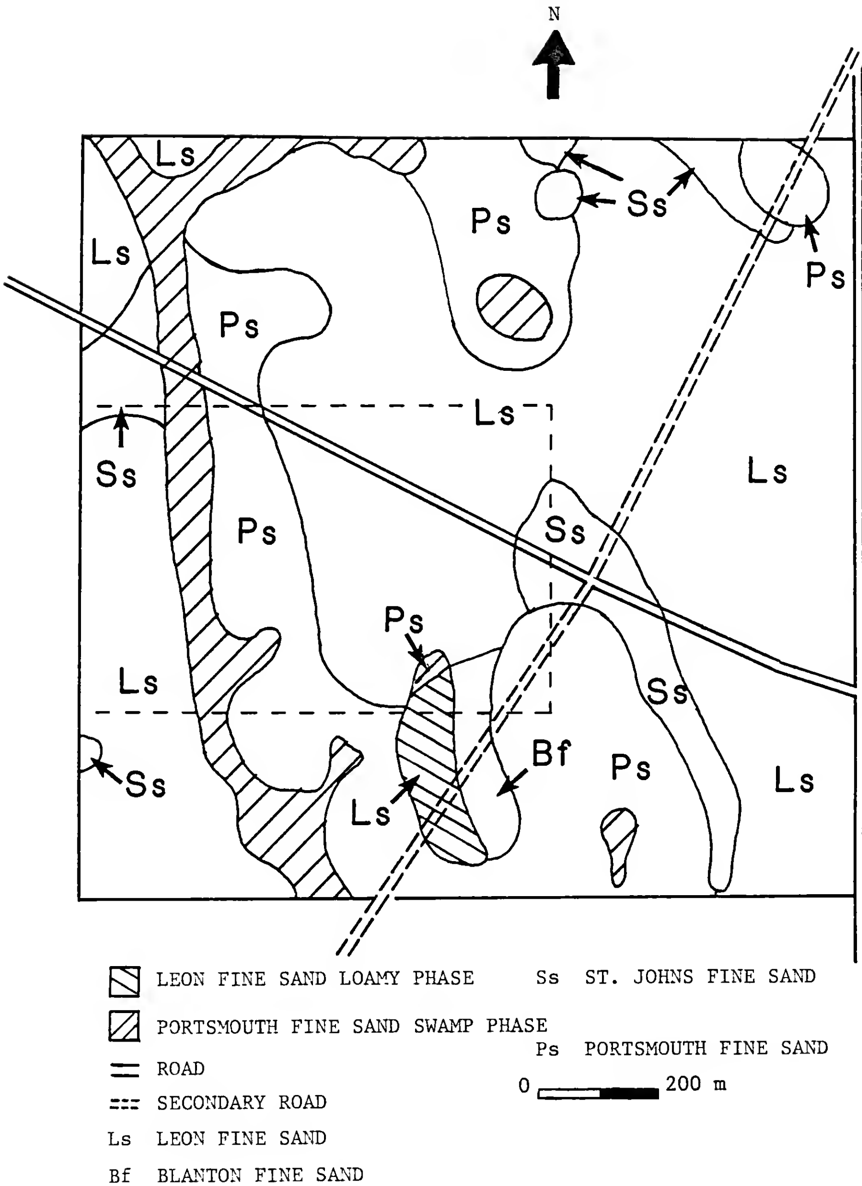


Fig. 6. Soil survey of the study site (inside dashed lines) and surrounding area from the 1927 Polk County Soil Survey (Soil Survey Staff, 1927).

phase, was split into four series, Wauchula, Wabasso, Pomona, and Eau Gallie, depending on depth to spodic horizon, depth to argillic horizon, and base status. Wabasso fine sand, a sandy, siliceous, hyperthermic Alfic Haplaquod, and Wauchula, a sandy, siliceous, hyperthermic Ultic Haplaquod, are loamy within 40 cm of the surface. Pomona sand, a sandy siliceous, hyperthermic Ultic Haplaquod, and Eau Gallie, a sandy, siliceous, hyperthermic Alfic Haplaquod are not loamy within 40 cm of the surface (personal communication, Richard Ford, Soil Survey Party Leader, USDA, Soil Conservation Service, Bartow, FL, January, 1984).

Sampling

The sampling scheme (Fig. 5), consisting of three nested regular grids, was designed for maximum use of geostatistics. The first sampling grid set up was rectangular, with its long axis parallel to the run of spoil as noted on older aerial photographs. The intent was to assess the variability of the population while minimizing the potential problems that might occur in sampling perpendicular to the spoil rows. Information from the first grid was used in designing one grid within the first grid with points spaced closer together, and another grid with points spaced farther apart that would fill the whole field.

The mid-sized grid, 50 m north to south by 200 m east to west, was situated in the northeast quadrant of the field. It consisted of six east-west (E-W) rows of 21

points each. The rows were 10 m apart and the points in each row were also 10 m apart (Fig. 5) (Bos et al., 1984).

The largest grid, 600 m north to south by 800 m east to west, consisted of 5 north-south (N-S) columns of 13 points each. The columns were 200 m apart and the points in the columns were 50 m apart (Fig. 5).

The smallest grid, comprising two connected, perpendicular 10 point transects, was situated on the western edge of the mid-sized grid (Fig. 5). The northmost point of the north-south transect was the westmost point of the east-west transect. Points in these transects were 1 m apart.

Samples from the mid-size grid were removed using a hydraulic coring tube or auger, depending on the amount of coarse fragments encountered. The coring tube was 7.5 cm in diameter, and the auger 12.5 cm. Sample cores were taken to 2 m unless (i) the presence of a shallow water table inhibited further sampling or (ii) ST was found at shallower depths. Two or three cores, if necessary to obtain sufficient volume of sample, were taken from each grid point and mixed together. The cores at each sampling point were taken as close together as possible to limit variability within each sample. The cores were split into 25 cm sections whenever distinct layers were less than 10 cm thick. Layers less than 10 cm thick would not yield enough sample for all of the chemical and physical analyses. The 25 cm thickness was adjusted a maximum of 10 cm up or down, if thick homogeneous layers were present, to avoid mixing of

such homogeneous layers with each other. One sample of the ST was taken whenever possible (Bos et al., 1984). Samples from the larger and smaller grids were taken from the surface only, using a 7.5 cm mud auger.

In using a sampling scheme based on set vertical distances rather than horizon characteristics, it was known that some potentially valuable information on variability would be lost because of the mixing of unlike layers into one sample. The original intent had been to use the properties of different materials in a profile, whether the materials were in one layer or many layers, as a criterion for characterizing minesoils. To save some of that information, estimates were made of volumetric quantities of materials different from each other in color and/or texture before drying and mixing of the sample. Abundance and sizes of roots were also noted (Bos et al., 1984). In many cases, the samples consisted of multiple thin (about 10 mm thick) layers of strongly contrasting materials (Fig. 7), making separation and analysis of each layer impossible. After drying, the samples were pulverized with an electric grinder, mixed, passed through a 2 mm sieve, and mixed again.

Specific overburden characterization data, whether pre- or post-mining, were not available. It was determined, therefore, that soil methods and procedures to be used should be those commonly used on native soils in the area.

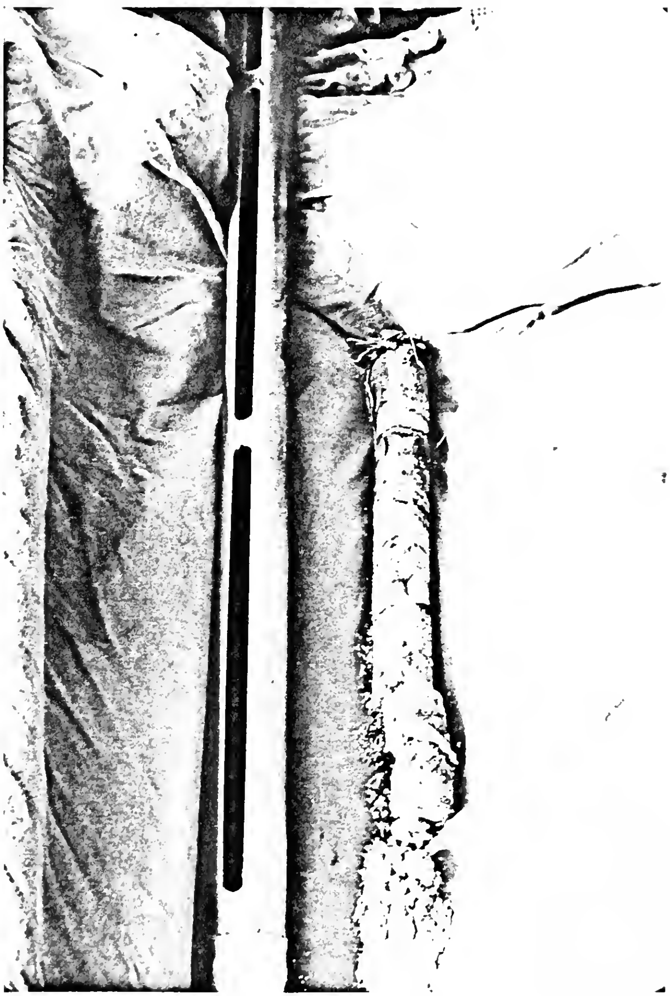


Fig. 7. Photograph of sampling tube (7.5 cm in diameter) and sample depicting the variability of color and texture in undisturbed samples immediately after being removed from sampling tube.

Procedures used by the Soil Characterization Laboratory, University of Florida, were chosen for this study.

Laboratory Analysis

Samples from the medium-sized grid were analyzed first. Bos et al. (1984) reported the procedures used on the surface samples from the medium-sized grid. Chemical analyses included H_2O-pH and KCl-pH (1:1 solution to soil), and cation exchange capacity (CEC) calculated as the sum of bases (Na, K, Ca, Mg) extractable by 1N NH_4OAC at pH 7 (Soil Survey Staff, 1972, method 5B1) plus acidity extracted with 0.5N $BaCl_2$ TEA pH 8.2 (Soil Survey Staff, 1972, method 6H1 + 6H1a). After doing the geostatistical work on these data (described here and by Bos et al., 1984), laboratory work continued.

Cation exchange capacity, KCl-pH and H_2O-pH, as described above, were completed on the rest of the surface samples from the larger and smaller grids. All surface samples from all grids were analyzed for percent organic carbon by the acid chromate digestion method (Soil Survey Staff, 1972, method 6A1) and for particle size determination by pipette slightly modified from the Soil Survey Staff (1972). The modification was the nonremoval of organic matter prior to analysis since the majority of samples contained much less than 1% organic carbon. Finally, subsurface samples from nine locations in the mid-sized grid were analyzed using the same procedures as before.

Samples of the yellow siltstone were also qualitatively analyzed by X-ray diffraction. Pebble-size material was ground with an agate mortar and pestle, a small amount of the powder was sprinkled onto a glass slide, and several drops of amyl acetate-collodion mixture were added to enhance adherence.

Geostatistics

Geostatistical analysis of the initial parameters (medium grid) consisted of calculations of semi-variograms and determination of structure (Bos et al., 1984). Two programs in Applesoft BASIC for the Apple II computer (written by R. Jessup, Soil Science Department, University of Florida) were used: (i) to calculate the direction-dependent and independent semi-variograms, and (ii) to fit one of the models to the calculated semi-variograms. The fitting was by visual estimate only. At this time, there was no testing of goodness-of-fit and no Kriging.

The search for a suitable Kriging program took several months. After many unsuccessful attempts at modifying programs from "Mining Geostatistics" (Journel and Huijbregts, 1978) to run at the North East Regional Data Center (NERDC), it was determined that these programs would not be immediately suitable for use. The next stop in the search was to the KRIGE subroutine in the "Surface II Graphics System" (Sampson, 1978). This particular subroutine is not available at the NERDC. Another commercial Kriging package could not be used due to

proprietary usage rights. The "Semi-Variogram Estimation and Universal Kriging Program" (Skrivan and Karlinger, 1979) was chosen because in addition to being "free of charge," it was easily modified to run at the NERDC. This program was used for geostatistical analysis and interpolation of 2000 points from the population of 204 values of each characteristic. This program consists of four options required for (i) calculating the semi-variogram, (ii) determining drift in the population, (iii) optimizing the semi-variogram, and (iv) Kriging, i.e., using the semi-variogram to estimate values at unsampled locations. Generally speaking, output from one option is either directly input into another option or is used to modify values input into another option. One intermediate step, described later, was used outside of the program to enhance the program's utility.

Before a valid semi-variogram can be calculated, the drift, if present, must be removed. If the local population mean varies geographically, it is said to have drift. Drift can only be determined, however, if the semi-variogram has already been calculated. This circular logic necessitates trial and error, with simultaneous calculation of the semi-variogram and its associated drift. The program makes use of this relationship by allowing the calculation of the semi-variogram on the residuals of the observations minus the drift. This is an iterative process of running options (i) (semi-variogram calculation) and (ii) (drift

determination), in sequence repeatedly. The general process is described below.

Data, consisting of x, y, and z values (geographic east-west and north-south and the associated parameter value), were input to option (i), which calculated direction-dependent and direction-independent semi-variograms and estimated drift.

Once the semi-variograms were calculated, the next step was to determine the structure of the semi-variograms. Structure analysis consists of fitting an equation with parameters A, ω, and C to the calculated semi-variogram curve. Ninety-five percent confidence intervals around the population variances were computed for each population of 204 values (elevation had 155) to indicate which semi-variograms exhibited pure nugget (Romano, 1977). This interval has been identified on each semi-variogram figure. In all cases, this interval excluded the nugget indicating significant structure (lack of pure nugget). The ability to fit the semi-variogram depends on the experience of the user plus the flexibility of the semi-variogram program. A program in Applesoft BASIC was used to fit one of the models to the calculated semi-variograms.

The models were chosen based on shape alone. No consideration of the physical significance of the different model types was given to the fitting procedure. There is little evidence to link models with particular distributions in the soil sciences.

Testing goodness-of-fit (GOF) of semi-variograms is not quite the same as testing GOF of other curves fit to data points on a graph. Typically, an R-square value is used to identify the spread of the graphed points about a curve. The semi-variogram (graphed points), however, can best be thought of as a guide to be used for the fitting. The variables A, C, and ω and equation types are, in fact, juggled to fit the graph, but the GOF procedures actually test the fit of the equation to the individual sample values. There is no evidence to suggest that a fit of an equation to the graph with the highest R-square will always result in the best fit to the actual sample values. This is the reason a visual fitting procedure was used to fit the equations to the graphs rather than a computational method. The GOF method used in the program is described later.

After calculating the semi-variogram, fitting the proper curve, and determining that drift may exist, the next step would have been to calculate the equation of the drift (option ii). In fact, option (ii) was attempted but not used for two reasons. The first reason is that, of the nine populations, drift was only noticed in elevation. The second reason was that the program documentation did not indicate how to use the output to choose the proper drift coefficients. It did indicate that trial and error was the best method. Considering that each estimate would have to be tested for goodness-of-fit, the costs involved outweighed

the benefit of getting a slightly better fit for the elevation semi-variogram.

In this study, several more limitations of the Skrivan and Karlinger program were noted but it is impossible to determine the degree to which these limitations adversely affected the analyses. The biggest single limitation was expense. Of the four program options, option (iii) (goodness-of-fit test) was the most costly to run. Option (iii) was used to determine goodness-of-fit of the calculated semi-variogram to the real semi-variogram. The procedure used is commonly called "jackknifing." Each data point was individually suppressed along with its associated row and column. The program then computed an estimate of that point using the semi-variogram model, drift coefficients, and the remaining points. The program calculated the Kriged average error (KAE) of the population, which was the difference between the real vs estimated values using the equation

$$KAE = \frac{1}{n} \sum_{i=1}^{n} (Z_i - \hat{Z}_i) \qquad (4)$$

where n = number of points,

Z_i = measured value,

$\hat{Z}_i$ = Kriged value.

The program also calculated Kriged mean square error (KMSE), using the equation

$$KMSE = \frac{1}{n} \sum_{i=1}^{n} (Z_i - \hat{Z}_i)^2 \quad . \tag{5}$$

Finally, the program calculated the Kriged "reduced" mean square error (KRMSE) using the equation

$$KRMSE = \frac{1}{n} \sum_{i=1}^{n} \frac{(Z_i - \hat{Z}_i)}{\hat{\sigma}_i} \tag{6}$$

where $\hat{\sigma}_i$ = standard deviation (error) of the Kriged point,

$$\hat{\sigma}_i = K(o) - \sum_{i=1}^{n-1} \lambda_i \sigma_{ij} - \sum_{i=1}^{m} \mu_i f_i(X_j, Y_j) + \sum_{i=1}^{n-1} \lambda_i^2 S_i^2 \tag{7}$$

where $K(o)$ = sill

λ_i = unknown weighting coefficient

σ_{ij} = covariance based on semi-variance and sill

S_i^2 = variance of the measurement error

μ = unknown LaGrangian multipler

$f_i(X_j, Y_j)$ = drift.

The KAE should approach 0 and the KRMSE should approach 1 as the fit improves. The decision as to how close the values should be to these ideal levels before being considered "good" is a function of the needs of the user.

Each population of 204 points had to be split into three approximately equal groups before entering into this option. These new smaller populations, south, east, and

west, were developed so that each would contain some points in the medium grid (Fig. 8). Only once were all 204 data points entered together. Five hundred seconds of computer time were not enough for the calculations to be completed. The high cost of each run reduced the number of times different equations or different parameters could be tested.

The problem of cost was most noticeable where a proper equation cannot be found or where drift is present. Each time drift or the equation parameters are changed, option (iii) had to be run to determine goodness-of-fit. Nine soil variables were of importance in this study. The maximum number of runs per parameter was limited to five. Equation parameters A, C, and ω were changed modestly to minimize KAE and to get KRMSE to approach 1 for each of the south, east, and west populations.

Periodicity exhibited in the semi-variograms remained unaccounted for because of another program limitation, the lack of flexibility in choice of models. Skrivan and Karlinger incorporated the most commonly used models in their program but did not add a model that may have resulted in a much better fit for the semi-variograms modeled here. Journel and Huijbregts (1978) described a "hole effect model" as one incorporating a sine or cosine function to model semi-variograms that are demonstrably cyclic. This model was not included as one of the choices in this program.

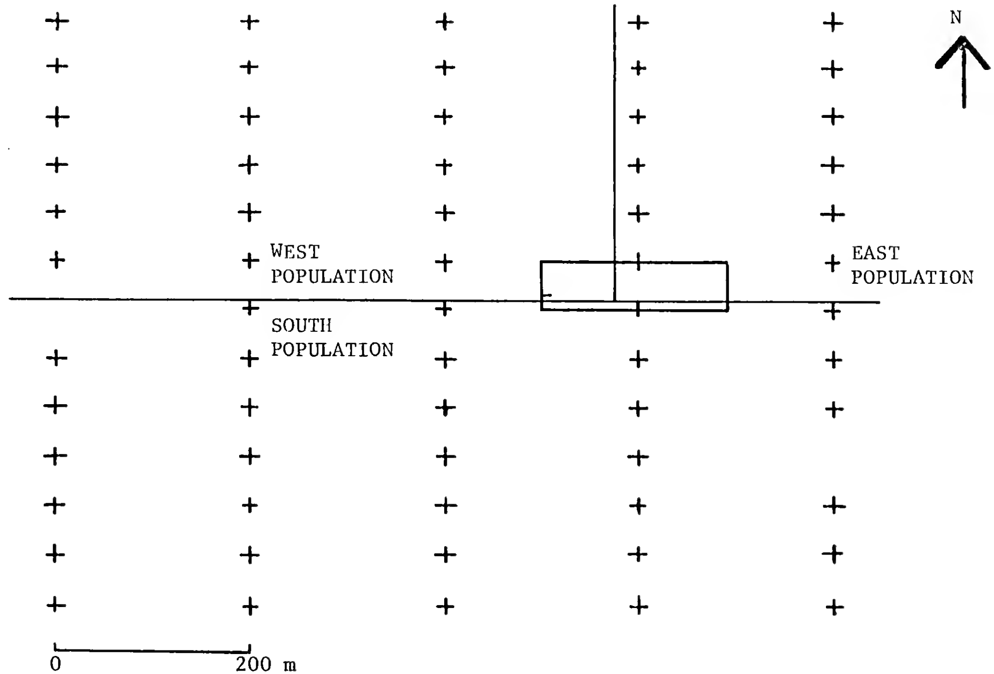


Fig. 8. Schematic of three nested grids showing where lines were drawn separating 204 values into east, west, and south populations for goodness-of-fit tests.

Another problem in the program was noted in the Kriging option which led to undesirable adjustments in structure determination. Although the program allowed direction-independent and direction-dependent semi-variograms to be computed, it did not allow for their combined use during Kriging when anisotropy was found to be present. The program accounts for the varying distances between the point to be Kriged and each of its neighboring points through the use of the assigned semi-variogram equation and parameters. The program does not have the capability, however, to use direction-dependent semi-variogram equations and parameters that would depend on the relative locations (directions) of the Kriged points and their neighbors. Because of this, only the direction-independent semi-variograms were modeled for use in the Kriging option. With much more time and effort, it may have been possible to determine the structure of each direction-dependent semi-variogram and arrange the locations of points to be Kriged to maximize the use of the direction dependence.

Another area of inflexibility in the Kriging option was the inability to determine an optimum neighborhood size. A neighborhood is the area of influence around the point to be Kriged. It is important to be able to pick the size of the neighborhood around the point to be Kriged so that a localized mean can be calculated rather than a general mean. Since the whole population was used in the estimation of each point, the population mean resulted when the

distance between the point to be Kriged and its neighbors was greater than the range of the semi-variogram.

Once KAE and KRMSE values were acceptably close to 0 and 1, respectively, the equation and the variables, data, drift coefficients (if needed), and x, y pairs of coordinates were input to option (iv) which calculated the Kriged z value for each x, y pair and its associated variance. Option (iv) was run twice for each parameter, once with 2000 xy pairs covering the whole field and again with 500 xy pairs covering a small part of the field including the northwest part of the medium-sized grid. These z values and associated errors (standard deviations) were then input to the SURFACE II mapping program to produce isoline maps of the different values and the associated errors.

All populations were tested for normality (Univariate procedure) (SAS, 1982) to identify whether the Kriged estimates would be the best linear unbiased estimators. Transforming non-normal populations to normal was not attempted for two reasons. First, Rendu (1978) stated that the assumption of normality was not often satisfied and that the decision of whether a population can be assumed to be normal is based on past experience and judgement. Since this study was the first attempt at using geostatistics on these data, there were no answers to the question, "How close is close (to normal)?" Secondly, Henley (1981) stated that Kriging transformed data resulted in sub-optimal,

non-linear, biased estimators. The decision to use the non-normal populations was based on a compromise of accepting the sub-optimal estimates from the Kriging of non-normal data versus finding a program to handle disjunctive Kriging and still risk sub-optimal results.

RESULTS AND DISCUSSION

Morphological Characteristics of the Minesoils

Differences existed between minesoils and native soils. Horizontal layers or horizons as exhibited by native soil profiles often were less common in minesoils than in native soils. The exception was noted on older minesoils (10-15 years) when a darker surface layer indicated the beginning of A horizon formation (Appendix A, profile 1, Payne Creek Site). Typically, the layers in a minesoil profile were uneven in thickness, had abrupt boundaries, and contained discontinuous inclusions of material quite different from the matrix in texture and/or color. The chemical, physical, and morphological characteristics of the minesoil result from the OB (native soil and substrata) properties, the sequence in which the OB materials were excavated and dumped, the way in which the OB fell out of the dragline bucket and came to rest, and the effects of subsequent earth moving during reclamation.

As the dragline operator digs through the OB, he moves the material to the previously mined cut, building long, parallel rows of spoil piles that are uneven in height. The morphology of the minesoil, particularly the layering, is largely a result of the dumping action.

If the minesoil profile is located in the middle of the pile, the layers, may be horizontal (Fig. 9, Situation A), or they may dip diagonally across the profile (Fig. 9, situation B). If the profile intersects an edge of the spoil pile, perpendicular to the right edge of (B), horizontal layering will be noted. If the profile face were stripped away, through (B) from left to right, the layers would seem to be closer to the surface.

Another morphological form commonly seen, the inclusions of discontinous bodies within layers, seemed to result from material rolling out of the bucket as it tipped and then continuing down the sides of the spoil piles. In profile, these bodies were circular, and in three dimensions they were more or less spherical. In all the profiles examined, these spherical inclusions were finer in texture than the surrounding matrix or contained enough organic matter to be darker than 3.5 in both value and chroma when moist. The higher clay content and/or organic matter content apparently afforded sufficient cohesion to these bodies so that they did not break up as they fell from the bucket.

The sequence of layers in a profile depends on the sequence in which the OB was dug, moved, and dumped. Except for this layering and occasional incipient A horizon formation, there seemed to be no vertical trend in minesoil properties. The presence of any particular layer in one part of the horizon seemed not to have a genetic relationship to any other layer. Adjoining layers frequently were

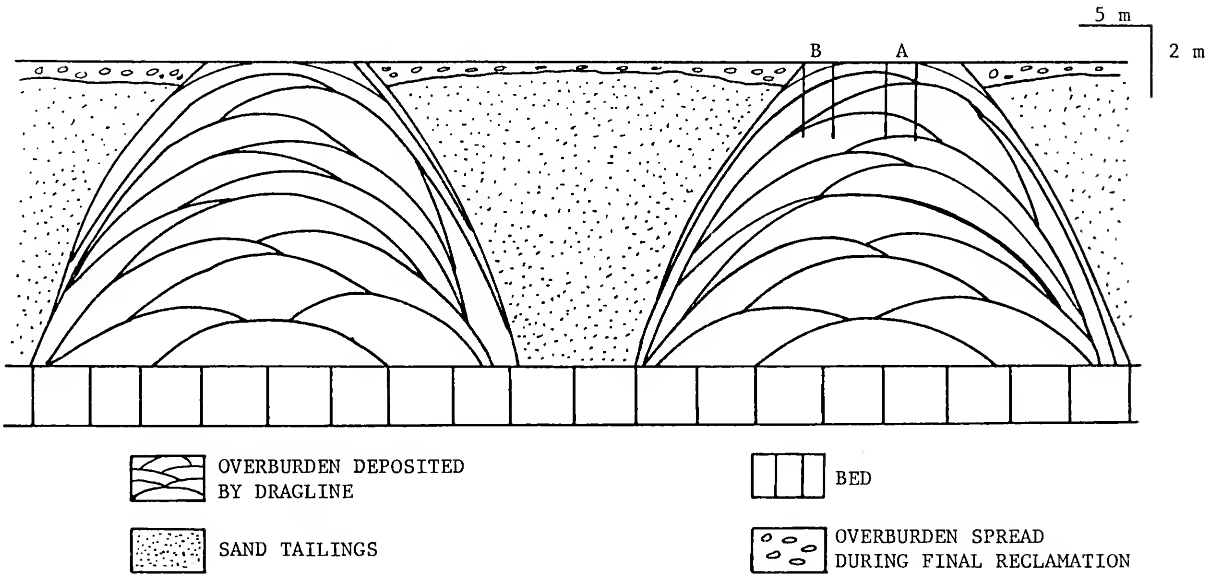


Fig. 9. Examples of hypothetical layer sequences in profiles A and B of phosphate minesoils.

quite different from each other. For example, a sandy clay layer might be found with a layer of sand above and an organic-rich layer below. The boundaries between the layers were abrupt and often very convoluted due to mixing during digging and dumping.

Specific Morphological Characteristics

Profiles 1 and 2 were somewhat alike but different from both profile 3 and the profile observed at the Fort Green site (Appendix A). The latter two profiles were somewhat similar. The difference involved the presence or absence of distinct layers. Profiles 1 and 2 exhibited layering, and the others did not.

Profile 3 and the Fort Green profile indicated a more complete mixing of the spoil. The Fort Green profile was located in an area where spoil had been spread over ST. Likewise, profile 3 was located near the sloping edge of the landmass, and represented material that had been pushed off of the center of the spoil piles during leveling procedures. Apparently, earthmoving operations subsequent to the initial mining caused a more complete mixing of spoil materials and resulted in the destruction of distinct layering. Spherical inclusions, however, were as common in the reworked material as in the top of profile 2. It was not known whether the spheres remained intact through the reworking or if new spheres were created as the more cohesive layers were once again moved. Profile 2 (Fig. 10)

Fig. 10. Photograph of profile 2, Payne Creek area, showing layering in the lower half and lack of layering in upper half due to effects of earthmoving after mining.

showed evidence of layering in the lower part; the upper part appeared to have been reworked during reclamation.

Although the gross morphology of the minesoil depends largely on mining and reclamation techniques, many physical and chemical minesoil properties depend also on the physical and chemical properties of the OB (native soil and substrata). Pre-mining OB characteristic data for this study site were not available. Data generalized for the whole area were available but were used only with caution.

The pre-mining OB consisted generally of a thick sand mantle over a layer of clay (Altschuler et al., 1964). The OB also included the noneconomic part of the matrix (i.e., that part called the leach zone). Presence or absence of this leach zone material and of dolomite was a major determinant of the character of the spoil (post-mining OB). If substantial amounts of dolomite occurred in the spoil, then the minesoil pH was near neutral. If dolomite was absent, while significant amounts of leach zone materials were present, vegetative productivity may be hindered due to low pH and/or aluminum toxicity. A site 19 Km east of the study area did not have dolomite in the spoil but did have enough leach zone material to induce aluminum toxicity symptoms in an Eucalyptus (Eucalyptus grandis) plantation (personal communiation, C.W. Comer, School of Forest Resources and Conservation, IFAS, Gainesville, FL, November, 1983).

Because of the great diversity of colors, textures, and morphology, initial characterization of minesoils was difficult. It was obvious in the initial reconnaissance that characterization could not be too rigorous. The problems involved the presence, absence, amounts, locations, or combinations of thin, distinct layers and the profile-spoil pile relationships already described.

Measuring layer thickness and distance from the surface did not yield useful information because presence, amounts, and locations of different materials in the profile appeared random. The descriptions of relative quantities of different materials per core sample retained, at least qualitatively, the variability lost in sample preparation (mixing, grinding, etc.). Field notes indicated the morphological differences between samples taken from a spoil island and samples taken from spoil on top of tailings. Comparison of field notes with laboratory observations and results showed that presence of weathered yellow siltstone was associated with a textural change from loamy sand to loam, and increased H_2O-pH and CEC. Field-lab comparisons also indicated that even though the majority of a sample was sandy in texture, the presence of clay lenses and spherical bodies of finer textured materials would cause texture of prepared samples to be finer than sand.

Minesoil Characteristics

A map of the sampling scheme was superimposed on an aerial photo (Fig. 11). This aerial photo was too old

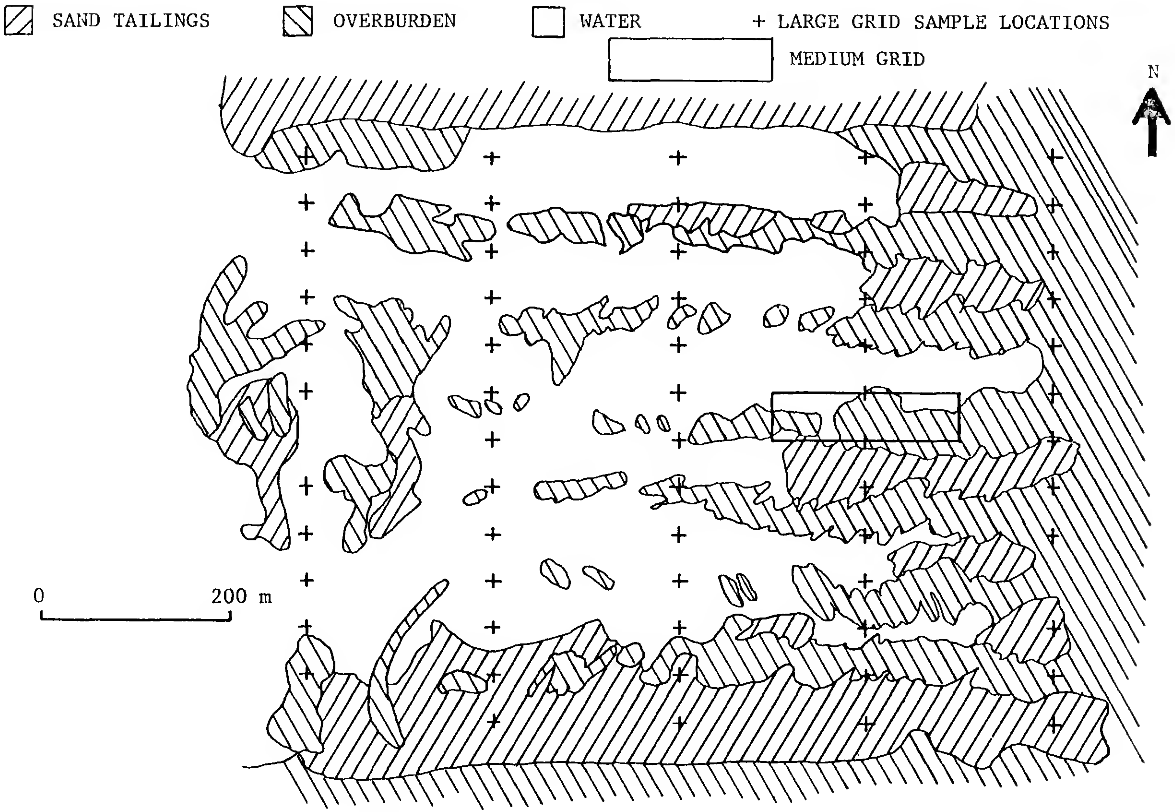


Fig. 11. Plan view of study site prior to reclamation and associated sample point locations.

(1979) to show the relationships of spoil and ST as they existed before final reclamation. The photo showed the site during ST filling, with the process only partially complete. The figure did show roughly, however, the relationship between sampling points and spoil islands. It was evident that the long rows of spoil of uneven height were already partially covered with ST, forming spoil islands. It was impossible to identify precisely all the spoil islands or determine how much of the spoil remained above the ST at the end of the filling stage.

Based on the measurements of depth to spoil-capped ST taken in the medium-sized grid, it appears that the spoil ridge underlying the eastern 2/3 of the medium grid largely was buried by the ST prior to leveling. The ST was closer to the surface on the northern half (Fig. 12) and deeper to the south.

On the southeastern edge of the medium grid, it was common to find a thin (3 to 30 cm) layer of ST somewhere in the profile. These layers usually contained more clay (field textures ranging from sand to sandy loam) than was found in ST elsewhere. This characteristic of higher clay content in ST just above spoil was observed elsewhere on the study site. The extra clay in the ST just above the spoil may have resulted from either the filtering of the clay from the first slurry water that passed by at the beginning of pumping or may have come from spoil sloughing into the ST as the ST slurry passed by the spoil piles.

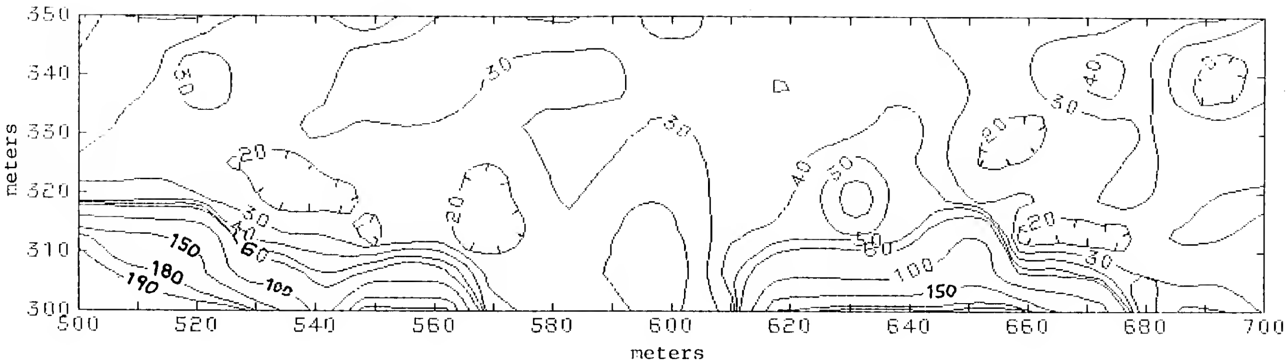


Fig. 12. Non-Kriged contour map of depth (cm) to sand tailings on the medium grid (350 = Row A, 300 = Row F).

The spoil island on the western part of the medium grid was not completely buried during the final stages of ST filling. In fact, this spoil island may have been the source of the spoil cover to the north in the medium grid. The results of the sampling scheme in this grid showed that there were chemical and physical differences in spoil characteristics depending on geographic position relative to the spoil islands, as will be discussed later.

The surface layer of the minesoil in this field was generally very slightly acid (Table 1). The H_2O-pH typically was about 6.6, but ranged from pH 4.8 to 8. pH values rather than H ion concentrations were used for statistical analyses (Shiue and Chin, 1957). Organic carbon (OC) content averaged 0.50%, ranging from 0.17 to 1.22%. Average cation exchange capacity (CEC) was 10.0 meq/100 g, ranging from 3.2 to 22.2 meq/100 g. Extractable acidity averaged 4.7 meq/100 g and ranged from 0.74 to 10.59 meq/100 g. Texture ranged from sandy loam to sand but generally was in the range of loamy sand. Bos et al. (1984) reported average double acid extractable Mg and K values of 300 mg/kg and 37 mg/kg and NH_4OAC extractable Mg and K values of 177 mg/kg and 41 mg/kg for samples taken from the medium grid. Average levels of NH_4OAC extractable Mg and K for the whole field were 2.1 meq/100 g (254 mg/kg) and 0.1 meq/100 g (38 mg/kg), respectively. Magnesium values ranged from 0.25 to 6.02 meq/100 g and K values ranged from 0.017 to 0.295 meq/100 g. Although the four bases Na, K, Ca, and Mg were

Table 1. Statistical moments of surface soil (25 cm) parameters.

Variable	Number of samples	Mean	Mode	Median	Range	Variance	CV %	Skewness	Kurtosis
Elevation, ft	155	23.6	24.4	24.4	8-26.8	11.76	14.5	-2.71	8.04
H_2O-pH	204	6.6	6.6	6.6	4.8-8.0	0.45	10.2	0.17	-0.95
KCl-pH	204	5.6	5.9	5.5	4.4-7.3	0.70	14.9	0.37	-1.07
Sand, %	204	83.1	84.3	83.6	60.1-95.5	22.5	5.7	-1.39	5.22
Organic C, %	204	0.47	0.31	0.45	0.17-1.22	0.03	36.4	1.26	2.40
Cation Exchange Capacity, meq/100 g	204	10.0	9.8	9.4	3.2-22.2	9.60	31.2	0.95	1.42
Extractable Acidity, meq/100 g	204	4.7	2.18	4.16	0.74-10.59	6.27	53.5	0.82	0.61
Extractable Mg, meq/100 g	204	2.1	0.77	1.31	0.25-6.02	2.77	79.8	1.37	7.12
Extractable K, meq/100 g	204	0.096	0.095	0.091	0.017-0.295	0.002	49.1	1.73	5.22

included in the CEC determination, only K and Mg were individually scrutinized. Potassium values appeared to correlate well with Na values and Mg values with Ca values.

The Univariate procedure indicated that none of the populations were strictly normal. H_2O-pH and KCl-pH populations were closest to normal. A population with a small CV may be best described by either a normal or lognormal distribution (Rao et al., 1979). Elevation and sand populations may fit into this category.

In addition to the analysis of data from surface soils, some data were analyzed on subsoil layers at selected sites. Averages were computed for nine locations sampled to 115 cm or greater depths in the medium grid (Table 2). The averages represent the sum of the layer values divided by the number of layers in each profile. These nine locations were chosen out of a possible 15 because all the layers in each of the nine profiles were very close to the 25 cm ideal length as described in the materials and methods section. These profile averages varied slightly from the grid-wide averages for surface soils, although it was not known whether the differences were significant or not. Since it was assumed that the sampling points were not random and independent, statistical analysis was not pursued. Trends were observed, however.

Surface soils, for example, had greater OC contents, more extractable Mg and K, higher CEC, and higher extractable acidity than subsurface soils. In surface soils

Table 2. Means of subsurface soil parameters by position and as combined means.

X	Y	H_2O-pH	KCl-pH	Sand (%)	Organic C (%)	Cation Exchange Capacity (meq/100 g)	Extractable Acidity (meq/100 g)	Extractable Mg (meq/100 g)	Extractable K (meq/100 g)
500	310	6.3	6.5	78.6	0.51	16.3	2.53	5.7	0.04
650	310	5.9	5.3	90.1	0.28	6.55	4.14	0.66	0.04
500	300	6.4	6.6	78.8	0.24	12.52	1.78	4.18	0.04
620	300	6.1	6.2	86.2	0.27	8.58	2.36	2.94	0.03
630	300	5.8	5.4	86.6	0.52	9.91	6.61	1.33	0.01
640	300	5.5	4.4	87.2	0.32	5.51	4.66	0.26	0.01
650	300	5.9	5.7	79.1	0.33	10.82	3.41	2.80	0.04
660	300	5.9	5.2	85.1	0.23	7.35	2.61	1.62	0.02
670	300	5.8	5.1	83.7	0.42	10.06	6.78	1.00	0.03
$\overline{X} \pm s$		5.9±.43	5.6±.99	83.9±8.9	0.36±.23	9.76±4.47	3.77±2.48	2.36±2.23	0.027±.02

and subsoils, KCl-pH was equivalent but H_2O-pH was higher in the surface soils. The surface soils had a slightly finer texture than those averaged over depth. Dolomite and fertilizer were applied during pasture establishment and probably account for some of the differences in H_2O-pH, KCl-pH, Mg and K contents between surface soils and subsoils.

The average OC content of the surface soils was greater than that of the subsoils, indicating incipient A horizon formation. Otherwise, there was no trend (increasing or decreasing) with depth. The sample found to contain the most OC occurred, in fact, at a depth of 175 cm.

Large differences between the averages were not expected because of the nature of material placement. The dragline operators did not segregate the OB materials according to likeness of properties, so there was just as much chance of having clayey and sandy materials next to each other as on top of each other.

Differences in spoil characteristics (slowly increasing or decreasing values) were noted locally, specifically within the medium-sized grid. All values except elevation were averaged by row, over the six east-west rows of sampling points (Table 3). Of these averages, only extractable K values did not show a regular increasing or decreasing trend across the rows. There were increases in KCl-pH, H_2O-pH, CEC, OC, and extractable Mg from row A southward with the highest values in either the E or F rows. Extractable acidity and sand contents decreased in the same regular manner as other values increased.

Table 3. Means of surface soil parameters by rows in the medium grid.

Row	H_2O-pH	KCl-pH	Sand	Organic C	Cation Exchange Capacity	Extractable Acidity	Extractable Mg	Extractable K
			%	%	meq/100 g	meq/100 g	meq/100 g	meq/100 g
A	6.05±.25	4.87±.34	83.8±2.0	0.46±.18	8.03±1.66	5.51±1.90	0.82± .24	0.08±.03
B	5.94±.17	4.80±.26	83.8±3.4	0.42±.13	8.74±1.85	6.26±1.98	0.83± .21	0.11±.03
C	5.99±.31	4.88±.41	83.3±1.8	0.46±.08	8.97±1.62	6.08±1.79	1.07± .75	0.13±.04
D	6.88±.48	5.43±.45	82.6±2.2	0.46±.13	9.91±1.46	5.40±2.38	1.81± .99	0.11±.04
E	7.04±.53	5.48±.48	81.2±7.3	0.52±.17	10.27±2.24	5.19±2.53	2.07±1.28	0.12±.04
F	6.97±.51	5.55±.39	82.8±6.6	0.54±.24	9.49±2.93	4.30±2.44	2.14±1.01	0.09±.03

One of the agronomically important aspects of creating this mine land type spoil-capped ST, is the manner in which the spoil is spread over the ST. The spreading process seemed to have caused the general trend in values from row A to F, in one of two ways.

First, there may simply have been differences in types of materials. It is possible that during mining, the last spoil dumped on top of the piles was sandier, slightly more acid, and relatively low in dolomite. During reclamation, as the bulldozers spread the spoil from the islands over the ST, this material was spread. This explanation is not highly plausible since, as noted above, the dragline operators do not segregate materials during mining.

A more likely explanation was that significant amounts of leaching occurred in the spoil between the time of mining and reclamation. Mining ended in 1976, and final grading of the site was not completed until 1980. This interval may have been long enough for the upper 1 or 2 m of spoil to be leached of some native, dolomite-derived Ca and Mg carbonates. The difference in Mg concentrations between rows A and F is 1.32 meq/100g, which roughly equates to 256 Kg per cubic meter of soil (assuming a bulk density of about 1.61 g/cm^3). If half of the yearly rainfall (140 cm) infiltrates and equilibrates with the dolomite (67 mg/l in solution), it will take about 5 years to leach the 256 Kg from the top meter of soil.

It was the upper, more leached spoil layers that were spread out over the ST. The spreading uncovered the less weathered spoil beneath. The spoil of rows A, B, and C consisted, therefore, of the more leached materials, and rows D, E, and F were dominated by the relatively unweathered materials.

Geostatistics

Values of certain soil parameters apparently depend heavily on location relative to spoil islands. It is important to design sampling schemes that correctly assess that relationship for this and similar fields. Part of the sampling design would be to study the spatial variability of individual parameters to determine how close together the sampling points must be to ensure that some points will fall on the spoil islands and some will fall between the spoil islands.

It is possible to determine an optimum sampling scheme that can represent the field soil parameters to any desired accuracy by using geostatistics. Geostatistical analyses show the interdependence of sample values and their locations in the field through the semi-variogram.

The semi-variograms (using all 204 values) of CEC, OC, Mg, and K were described by spherical models (Table 4). Semi-variograms of H_2O-pH, KCl-pH, and extractable acidity were described by exponential models. The elevation semi-variogram was best described by a parabolic model, and the sand semi-variogram by a Gaussian model. The nugget

Table 4. Semi-variogram equation types and variables for each soil parameter using all sample points.

Variable	Equation Type	Omega	A	C (nugget)	Range (meters)	Sill
Elevation	Parabolic	1.5×10^{-3}	1.75	0	-	-
H_2O-pH	Exponential	0.52	35	0.04	105	0.56
KCl-pH	Exponential	0.70	75	0.18	225	0.88
Extractable Acidity	Exponential	3.85	37	2.75	111	6.60
Cation Exchange Capacity	Spherical	3.8	150	5.8	150	9.60
Organic C	Spherical	9.0×10^{-3}	90	0.021	90	0.03
Extractable Mg	Spherical	2.5	120	0.8	120	3.30
Extractable K	Spherical	1.1×10^{-3}	400	1.5×10^{-3}	400	2.6×10^{-3}
Sand	Gaussian	7.0	120	17	208	24

variance, range, sill, anisotropy, and drift were the important parts of structure determination. They provided information on the sample population plus the adequacy of the sampling scheme.

A semi-variogram with a non-zero intercept indicates presence of a nugget variance. The nugget variance in this study ranged from 0 for elevation to 17 for sand content (Table 4). A nugget of zero indicated that all variablity was associated with position, which was accounted for by the sampling scheme. The higher nugget variances for the other parameters indicated that the samples were not taken close enough together to eliminate all positional variability.

Even though some of the nugget variances were relatively close to the sill values (i.e., pure nugget effect), all of the semi-variograms did exhibit structure. A 95% confidence interval around the population variance (not part of the geostatistics package) was calculated for each sill value and in every case excluded the nugget value. There was a chance that these nuggets were artificially high since the smallest lag interval tested was 7 m. A distance of 7 m was used as the smallest lag because any smaller lag distances did not have enough pairs to adequately support the semi-variance at that distance. Twenty samples taken 1 m apart were not enough to influence the semi-variance at the first lag. The nugget variance also indicated the occurrence of some randomness among sample values independent of position. This randomness may

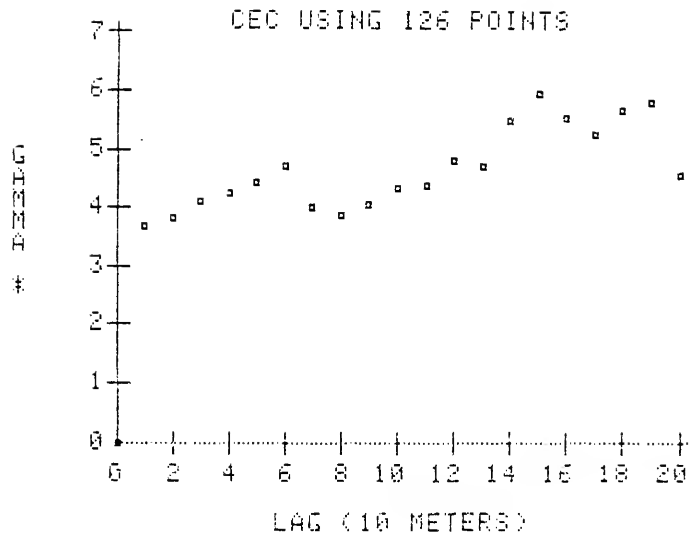
be due to one or more of (i) true, position-independent variability in the field, (ii) sampling error in drawing subsamples for lab analyses, and (iii) error in analytical measurement.

Range values indicate the distance beyond which pairs of samples are independent. Ranges varied from 90 m for OC for 400 m for extractable K (Table 4).

Just as Gajem et al. (1981) found different ranges and sills of the semi-variograms depending on the spacing between samples, differences were noted in this study between the ranges and sills as calculated for the first 126 samples (the medium grid) versus the total number of samples. The range and sill of the semi-variograms calculated for all points increased from those ranges and sills calculated for the first 126 points.

It is impossible at this time to identify whether measurement bias (Jury, 1984) or the spatial structure of the soils has a greater effect on the increased range that occurred in going from 126 to 204 values. The structure may also result from the unequal numbers of samples taken from the three different grid spacings.

The most significant differences involved the shapes of the semi-variograms of CEC and elevation. Bos et al. (1984) reported a pure nugget of 4.5 for CEC (Fig. 13) and a Gaussian curve for elevation (Fig. 14) with no range or sill. The semi-variogram of CEC, with all 204 values



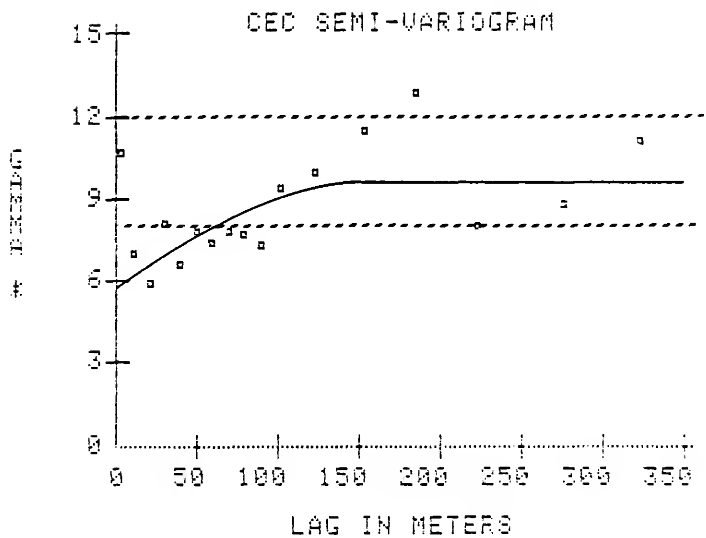
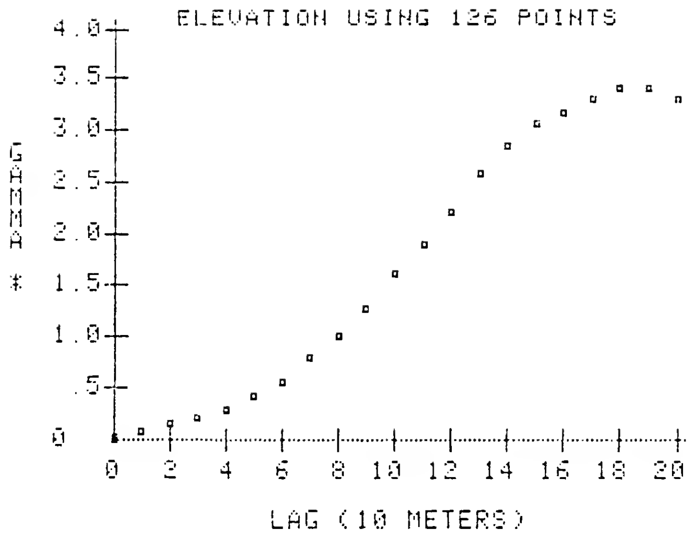


Fig. 13. Cation exchange capacity direction-independent semi-variogram calculated from 126 values (medium grid) (modified from Bos et al., 1984) and from all 204 values.



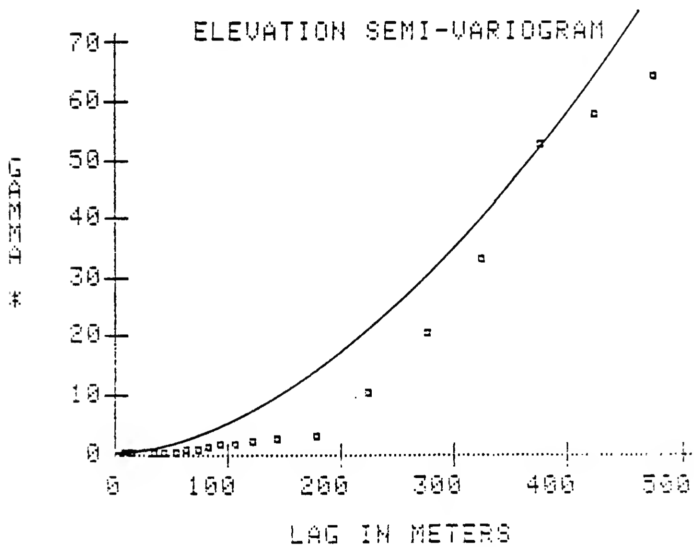


Fig. 14. Elevation direction-independent semi-variogram calculated from 126 values (medium grid) (modified from Bos et al., 1984) and from all 155 values.

included, was described by a spherical model with a range of 150 m and a sill of 9.6 (Fig. 13). The semi-variogram of elevation still had no range and sill but was best fit by a parabolic curve (Fig. 14).

When a semi-variogram exhibits a pure nugget, it usually indicates that the samples were not spaced closely enough to show any kind of structure. It appeared that the sampling scheme used in this first study was inadequate to show either the smaller-scale or the larger-scale structure for CEC. The addition of the values from the second phase of sampling showed a structure on a field-sized scale. The 60 widely spaced samples completely masked the pure nugget and any effects of the 18 samples spaced 1 m apart. The nugget of the new semi-variograms was larger than the pure nugget (sill) of the first and the new sill, 9.6, was twice as large as the old sill.

The different results show the need of choosing a sampling scheme such that the number of closely spaced samples is equivalent to samples spaced farther apart (e.g., 65 samples in the small, 65 in the medium, and 65 in the large grids). This kind of sampling scheme will identify the structure much better than a system with different numbers of samples at varying distances. In the present study (18 samples in the small, 126 in the medium, and 60 in the large grid), the best alternative was to choose the limits of lag distance classes that the computer would use to calculate each point of the semi-variogram. This

resulted in combining several odd distance classes together so that the numbers of pairs supporting each semi-variance were equal. These odd distance classes invariably masked some semi-variogram structure that would have otherwise been noticed.

The change in the elevation semi-variogram from Gaussian to parabolic does not seem significant at first glance. Bos et al. (1984) correctly reported only the first half of the elevation semi-variogram, which did not show any noticeable shape. The Gaussian shape is most noticeable if the same semi-variogram is shown to 200 m (Fig. 14). Although as much confidence could not be placed on the second half of the semi-variogram as on the first half, it was still possible to see the tendency for the curve to level out at about 180m. Comparing this to the parabolic shape of the semi-variogram of all values (Fig. 14) showed a much more significant difference. The new semi-variogram showed no tendency to level out.

The difference between these two semi-variograms was clearly caused by the presence of the slope in the field. All 126 samples used in the calculation of the first semi-variogram were on one of the level parts of the field. The majority of the added samples were located on the sloping land. The mean value of elevation decreased from the north-central part of the field (medium-grid) across the slope to the southern border. If this trend in the means could have

been removed, an entirely different semi-variogram might have been calculated.

Two other pairs of semi-variograms were compared, KCl-pH and H_2O-pH. The ranges of the semi-variograms calculated on the samples in the medium grid were 40 m for KCl-pH (Fig. 15) (Bos et al., 1984) and 45m for H_2O-pH (Fig. 16). Both ranges increased for the semi-variograms calculated for all 204 values to 230 m for KCl-pH (Fig. 15) and to 140 m H_2O-pH (Fig. 16). The sill decreased from 0.3 to 0.25 for KCl-pH but increased from 0.4 to 0.56 for H_2O-pH. Again the differences between the semi-variograms of 126 values versus the semi-variograms of 204 values emphasize the effects that changes in sample numbers and spacings have on the ranges and sills.

Two ways that ranges can be used are as follows. First, in order to use statistical analyses on OC sample values, for example from a site with equivalent soils, the samples must be taken 90 m apart (Table 4) to be considered independent from each other. The population will have a variance approximately equal to the sill. Second, in another situation, say determining organic carbon content for pesticide adsorption studies on similar soils, OC values with a smaller variance, 0.026, may be needed. If so, then samples should be taken about 35 m apart, inside the range, to have the necessary variance. The relationship between the variance and distance is shown by the equation fit to each semi-variogram during structural analysis. It is this

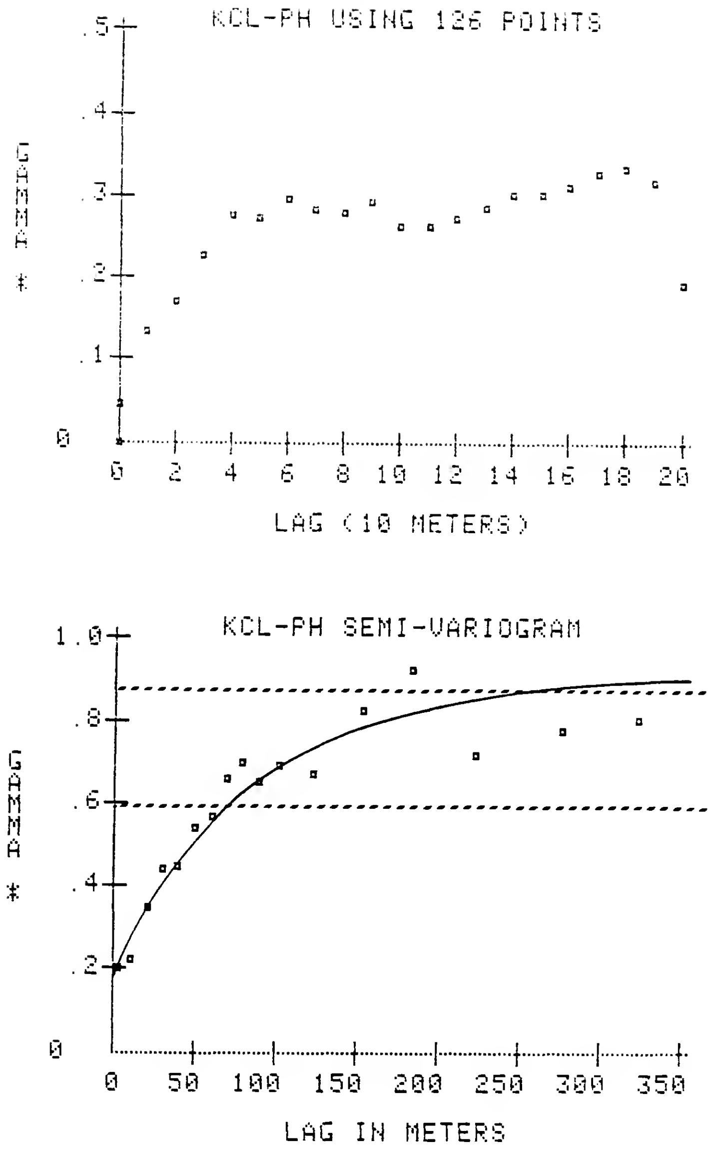
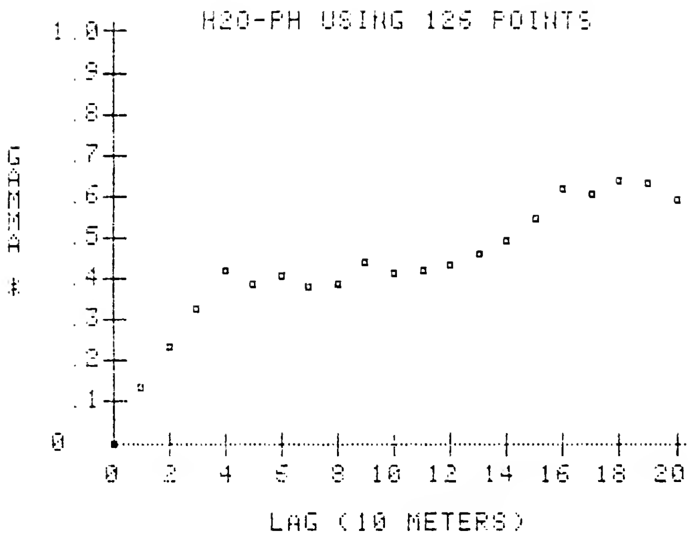


Fig. 15. KCl-pH direction-independent semi-variogram calculated from 126 values (medium grid) (modified from Bos et al., 1984) and from all 204 values.



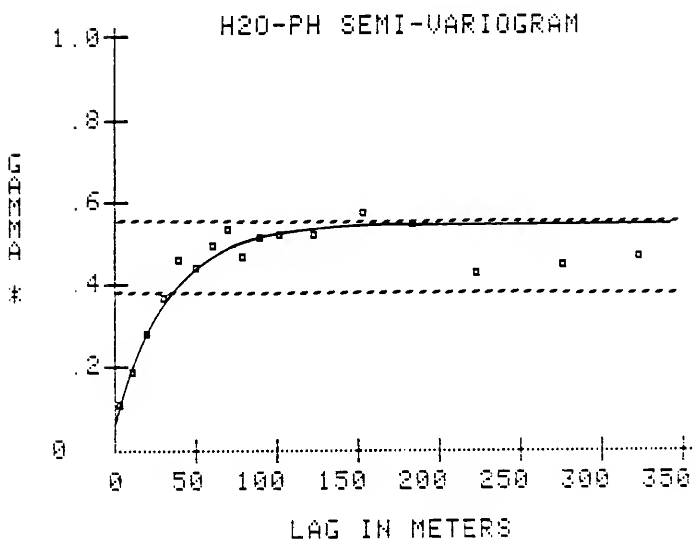


Fig. 16. H_2O-pH direction-independent semi-variogram calculated from 126 values (medium grid) and from all 204 values.

relationship that is used to find out how far apart samples must be taken in order to have a variance smaller than the population variance.

Theoretically, the sill of the semi-variogram should equal the variance of the 204 values. This does not always happen because just as the calculated variance (s^2) is an estimate of the true variance (σ^2), the calculated semi-variance (γ^*) is an estimate of the true semi-variance (γ). The sill and variance were essentially equal for OC and for CEC. The sill was slightly higher than the variance for H_2O-pH, KCl-pH, sand, and extractable acidity, Mg, and K for undetermined reasons (Tables 1 and 4).

Regional trend was a problem for elevation. None of the other semi-variograms exhibited an increasing semi-variance with increasing h. On the other hand, all semi-variograms except elevation exhibited some local trend that appeared cyclic. In most cases, there were inflections in the semi-variograms at 70, 140, 200, and 490 m. It is possible that this periodicity was caused by the sampling scheme and/or the grouping of lag distances. The lag distances can be grouped in any way the user wants but the preferred way is to group the lags so that the numbers of pairs contributing to each γ^* in the semi-variograms are equivalent. Such grouping was employed here.

Clark (1979a) showed the influence of varying sampling distances on semi-variogram periodicity. Periodicity might have vanished in the semi-variograms calculated in this

study with a different grid setup. A 50x50 m regular grid instead of the 200x50 m grid with the nest of 126 in the northeast quadrant might have eliminated the periodicity.

Since the semi-variograms are additive, the direction-independent semi-variograms will reflect the nuances of the direction dependent semi-variograms. If this were the case here, then the various inflection points in the direction-independent semi-variograms would have been due to anisotropy rather than to local drift. The majority of the direction dependent semi-variograms showed varying amounts of "non-smoothness," but the inflection points were always in the same position along the x axis. Because the inflection points were noticeable in all the direction-dependent semi-variograms, the majority of the structure was probably caused by drift rather than anisotropy.

Bos et al. (1984) found that the first sampling scheme of 126 samples was not adequate to identify anisotropy. We found that there were too few pairs of points in all directions except east-west to place confidence in the semi-variograms past the first two or three lags.

The addition of samples in the large grid enabled the calculation of direction-dependent semi-variograms of sufficient length to test for anisotropy. Anisotropy was exhibited in half of the parameters (H_2O-pH, KCl-pH, sand content, CEC, and extractable Mg). For these parameters, anisotropy was exhibited predominantly in the diagonal directions, northwest to southwest and northeast to

southwest. For example, compare the first 12 points in the Mg northeast to southwest semi-variogram with the same 12 points in the Mg northwest to southeast semi-variogram (Fig. 17). The former had average $\gamma^*(h)$ of about 4.0 and the latter about 1.0. It was also evident that one of the semi-variograms lay above the direction-independent curve (Fig. 17) and the other was below it. This placement, one above and one below, may have contributed to the smoothness of the Mg direction-independent semi-variogram, since the influences of these diagonal semi-variograms may cancel out one another. The three corresponding semi-variograms (Fig. 18) for extractable acidity did not reflect anisotropy, since they had approximately the same shapes. The north-south semi-variograms of all parameters exhibited the most scatter of any direction-dependent semi-variograms.

Even though the largest grid was designed to increase the number of points in the north-south direction (13 points north-south versus 5 points east-west), it could not compensate for the variability caused by the uneven rows of spoil and ST. Semi-variance was greatest when increasing numbers of pairs used in the calculations had one member of the pair on the spoil island and the other member off of the island. The greatest chance of this happening was found in the north-south direction because of the east-west pattern of the spoil islands.

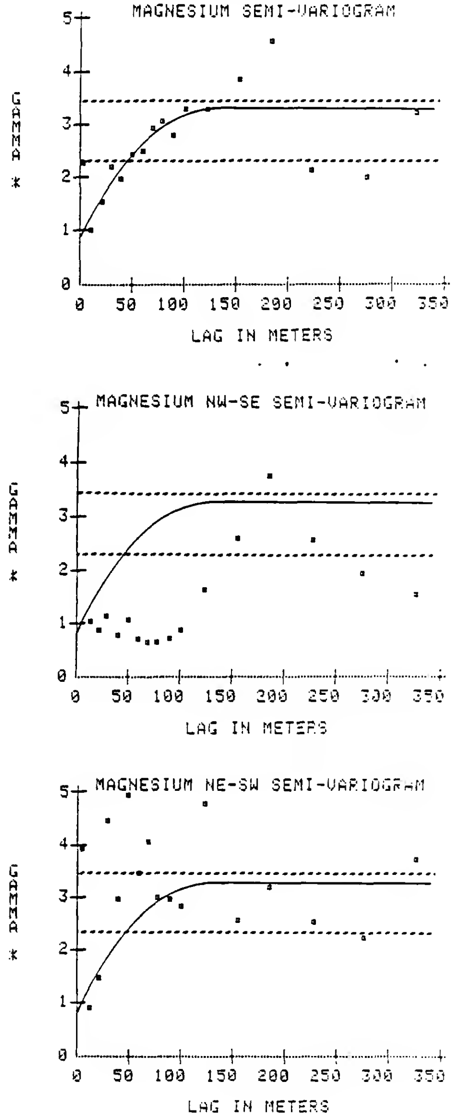


Fig. 17. Extractable Mg direction-independent, northwest to southeast, and northeast to southwest semi-variograms calculated from all 204 values.

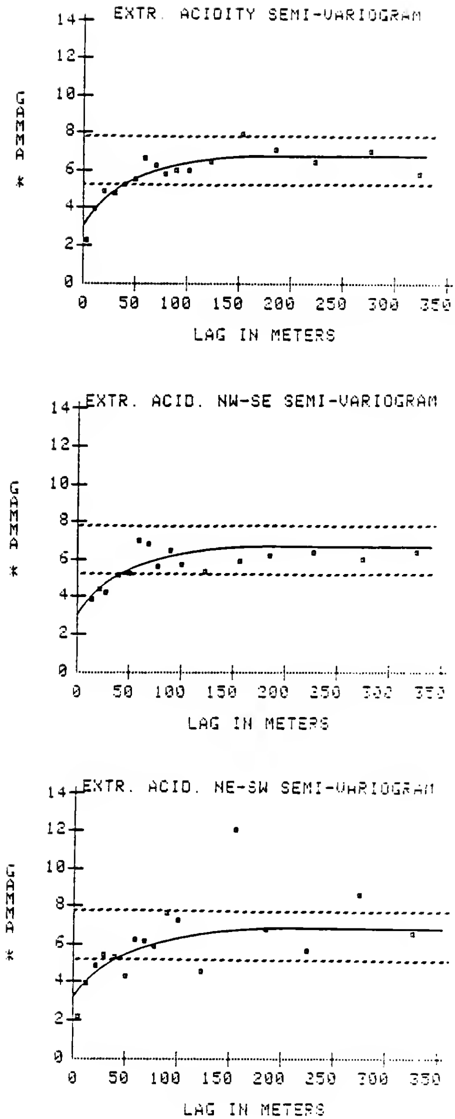


Fig. 18. Extractable acidity direction-independent, northwest to southeast, and northeast to southwest semi-variograms calculated from all 204 values.

Although the reason for dividing the populations was to reduce costs, the extra GOF numbers for each population added some information that may have been lacking otherwise. For example, the south data sets consisted mostly of widely spaced sample locations. The GOF numbers for these data sets may represent the predictive ability of the semi-variogram equation at such large distances. The west data sets and the east data sets included samples that were both widely spaced and closely spaced to test the semi-variogram equation.

Since the elevation data set contained fewer samples than the other data sets, it was divided into only two subsets which in this case were not equivalent. The west values included most of the widely spaced samples, and the east values included most of the closely spaced samples. The west GOF numbers indicated the poorest fit of any parameter subset. The poor fit was probably caused by the drift that could not be accounted for by this program. The true semi-variogram cannot be found if the drift cannot be removed. It is possible that a different equation from the one used here would have been more appropriate but cannot be determined until the drift is removed.

The east data set consisted of closer spaced samples than the west and was regenerated with much less error. Because of the closer spacing between adjacent samples, there were larger numbers of influential neighboring values, which led to a more precise fit.

For the rest of the parameters, GOF numbers appeared to be quite good (Table 5). The KAE values were less than 1% of the mean for all parameter subsets and, except for elevation, the KRMSE values were all close to 1.0. Organic carbon and extractable K populations had the best GOF numbers of any parameters. Direction-dependent semi-variograms of OC and extractable K were the least anisotropic and, except for the north-south semi-variograms, the most stationary of all population semi-variograms (Figs. 19-20).

Extractable acidity had KRMSE values very close to 1, but the KAE values were not close to zero relative to other populations KAE's. In fact, for the three subsets, the more closely KRMSE approached 1, the more negative KAE became. Cyclic, local nonstationarity probably caused the average error to be relatively high. Lack of smoothness in the data, therefore, inhibited the ability of Kriging to regenerate the values.

As the mean square error increases, the semi-variance should also increase, giving the expected KRMSE value of 1. Since the semi-variance of the extractable acidity was high, the KMSE can also be high and the KRMSE will still approach 1. It appears that the GOF values of KAE and KRMSE may be misleading. A KAE of 0 says only that the Kriging system overestimates the measured values as often and to the same degree as it underestimates them. It does not say how far away the estimate is from the real value. The KMSE does

Table 5. Goodness-of-fit values for each soil characteristic subset.

Variable		Subset East	Subset West	Subset South
Elevation	KAE*	0.0015	0.087	
	KMSE**	0.1835	2.7294	
	KRMSE***	1.3367	4.206	
H_2O-pH	KAE	-0.0036	0.0043	-0.0036
	KMSE	0.3203	0.4363	0.4343
	KRMSE	0.6898	0.9650	0.6212
KCl-pH	KAE	0.0116	0.001	0.0169
	KMSE	0.3883	0.5264	0.4769
	KRMSE	0.6394	0.8605	0.6256
Organic Carbon	KAE	0.0012	0.0006	-0.0023
	KMSE	0.1694	0.1517	0.2015
	KRMSE	1.0446	0.9546	1.2158
Sand	KAE	0.0121	0.040	0.0135
	KMSE	2.885	4.60	5.9267
	KRMSE	0.676	1.0778	1.3075
Cation Exchange Capacity	KAE	0.0086	-0.0259	0.0107
	KMSE	2.0434	2.7182	3.6422
	KRMSE	0.7533	1.0381	1.2494
Extractable Acidity	KAE	-0.0213	-0.0085	-0.0292
	KMSE	2.2940	2.0061	2.3082
	KRMSE	1.0724	0.9357	1.0357
Extractable Potassium	KAE	-0.0004	-0.0005	-0.0003
	KMSE	-0.0378	-0.0458	-0.0502
	KRMSE	-.9145	1.1113	1.0978
Extractable Magnesium	KAE	0.0115	-0.0189	0.0215
	KMSE	0.5245	1.0397	1.3593
	KRMSE	0.4306	0.9295	0.8376

* KAE = Kriged Average Error
** KMSE = Kriged Mean Square Error
*** KRMSE = Kriged Reduced Mean Square Error

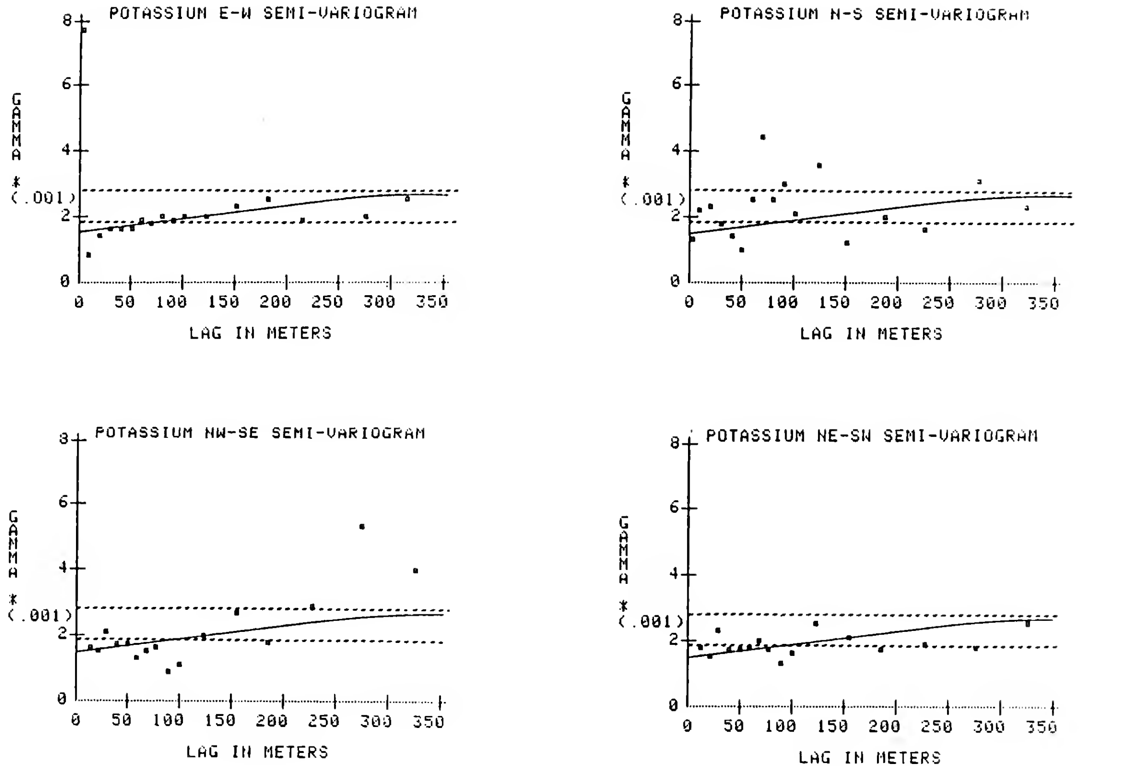


Fig. 19. Extractable K direction-dependent semi-variograms calculated from all 204 values.

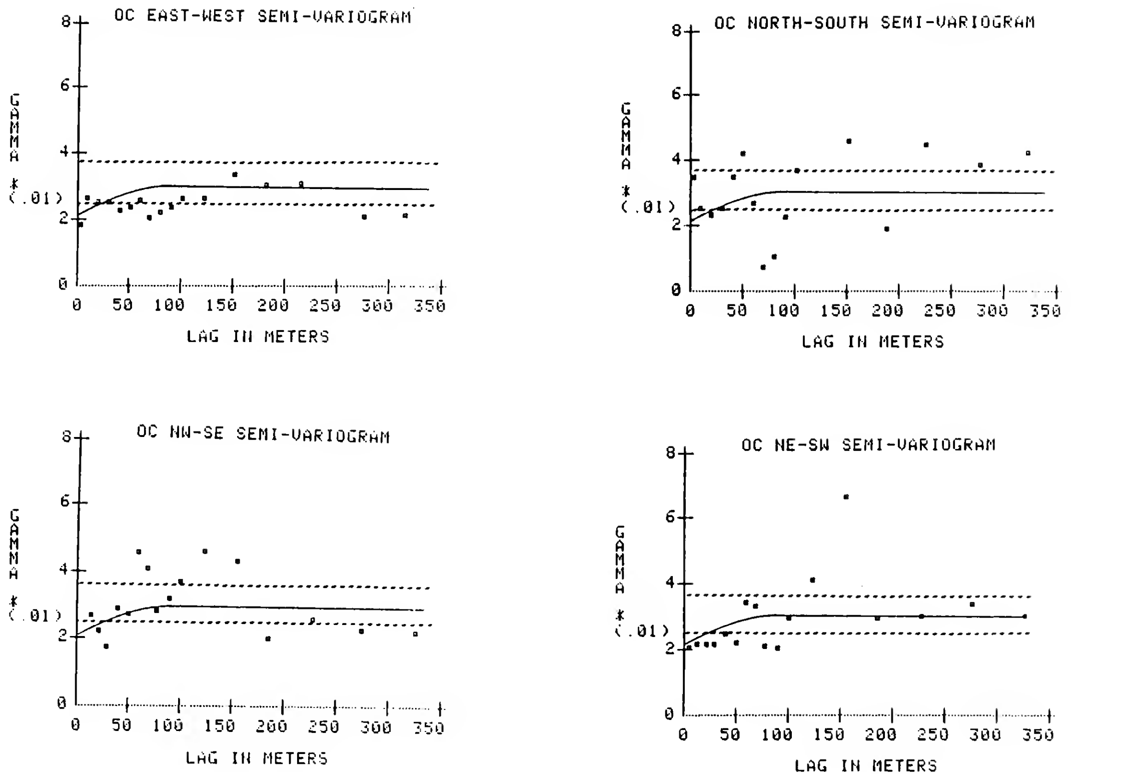


Fig. 20. Organic C direction-dependent semi-variograms calculated from all 204 values.

give a measure of the difference between estimates and real values.

Although a KRMSE of 1 is optimum, the KRMSE of 1 for a parameter with a small nugget is much more reliable than a KRMSE of 1 for a parameter with a large nugget. Kriged estimates will correlate much better with measured values if the semi-variogram has a smaller nugget than if it has a larger nugget. The KRMSE of 1 says only that the KMSE increases at the same rate as the standard deviation (error) of the measurements, independent of whether or not both values are large or small.

Contour Mapping

Drawing contour maps of the parameters was the final step to the Kriging process. Two objectives in doing the mapping were (i) to find out which parameters exhibited equivalent contours and (ii) to find out how well the parameters' contours corresponded to the spoil islands.

It was hypothesized that parameters showing similar patterns of contours would be somehow related to each other and in this case also to the location of the spoil islands. The computational methods that would best define the relationships between different soil properties include cross-semivariograms, cross-autocorrelograms, and co-Kriging. These were not attempted due to the lack of computer programs. Instead, the maps were compared visually.

The parameters most closely related to the position of the spoil islands should be those that showed the trend between rows A and F in the medium grid. Two maps were drawn for each parameter; (i) to identify the contours over the whole field (large grid) and (ii) to observe closer detail around and including part of the medium grid (small maps).

The most striking characteristic of the large grid maps was the way the contours depended on the actual sampling locations. This characteristic was most notable on the OC map, was exhibited only slightly on maps of extractable K and sand content, and was absent on elevation maps. Small range values for the OC semi-variogram equations appear to have caused this effect. Organic carbon had the smallest range of any parameter. Elevation did not exhibit a range.

The advantage of Kriging over some other interpolation schemes is that Kriging can remove some position-related variability from the total variability. Inside of the range, a point on the semi-variogram represents the value equal to the population variance (sill) minus the variance of points spaced a distance apart. Theoretically with less variability in the estimates, Kriging can result in better interpolation but only inside the range of the semi-variogram. Outside of the range, where positional variability is unaccounted for, Kriging is no more accurate than other interpolators. Outside of the range, the

influence of neighboring values is also diminished and the error associated with the estimate is at a maximum.

An interesting effect of this phenomenon was found on the maps of OC, extractable acidity, H_2O-pH, and extractable Mg (Figs. 21-24). The areas generally corresponding to x=100, 300, 500, and 700 were devoid of contours and were associated with the average value of each population. The associated error in these areas was equal to the standard deviation of the populations.

These areas were not sampled and were the farthest away from the sample locations (about 100 m). One-hundred meters was the approximate range of the variables exhibiting this phenomenon (Table 4). Since the samples in these locations were at or beyond the ranges of the semi-variograms, the optimum error was the standard deviation of the population. In addition, there were no influential close neighbors, so the program considered all values in the population to be part of the neighborhood of every estimated point in these areas. If it had been possible to choose a neighborhood of varying size for the estimations, the local averages would have been calculated instead.

Another general observation was that the location of the medium grid was found in most of the maps by looking for the most contours. The increased level of definition was caused by the tighter grid spacing in this area, which gave more accurate measurements.

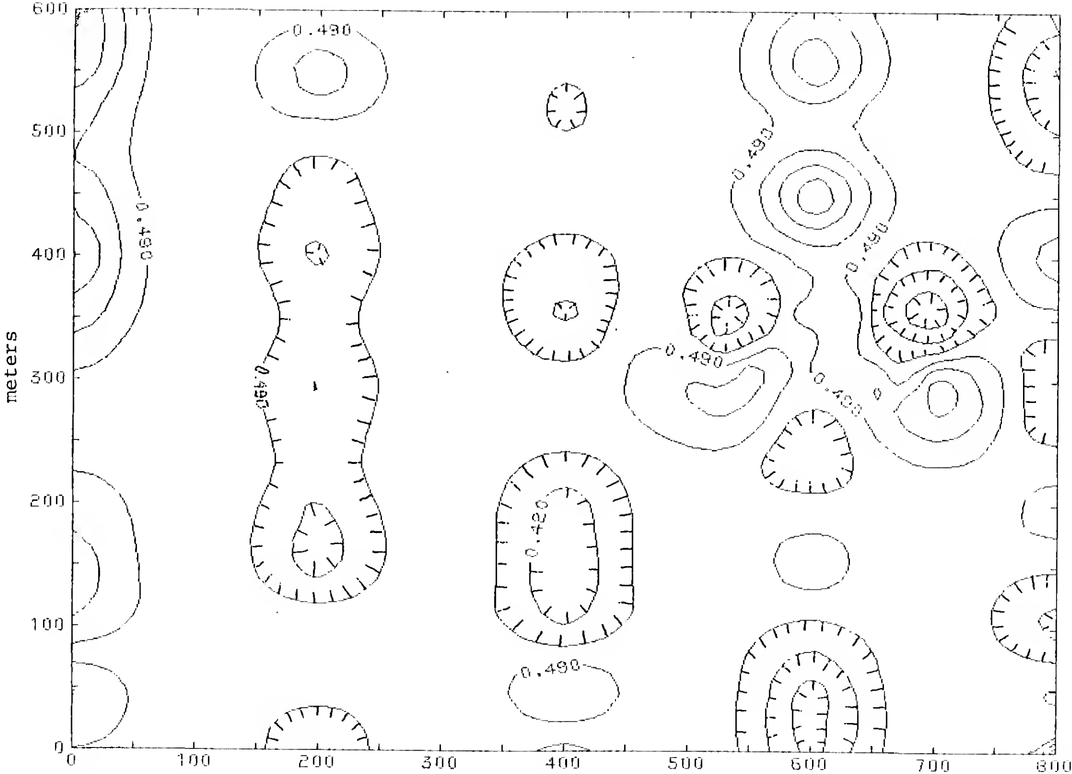


Fig. 21. Kriged organic C, large grid (increment is 0.035%).

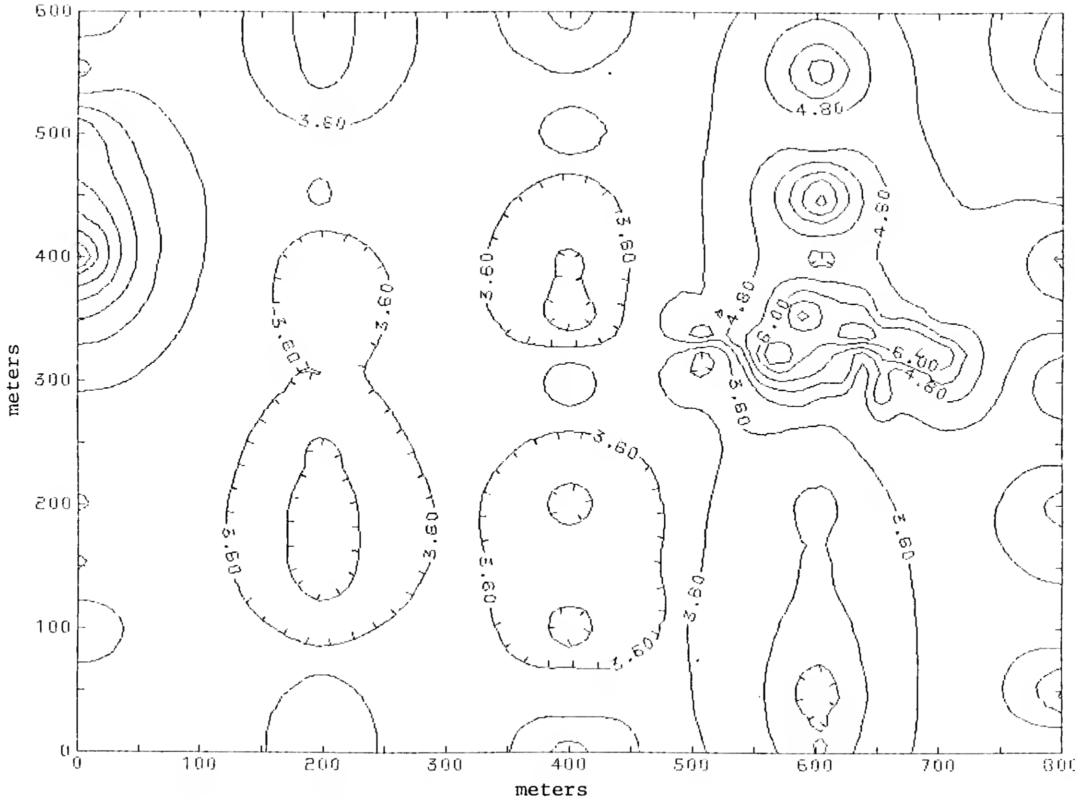


Fig. 22. Kriged extractable acidity, large grid (increment is 0.60 meq/100 g).

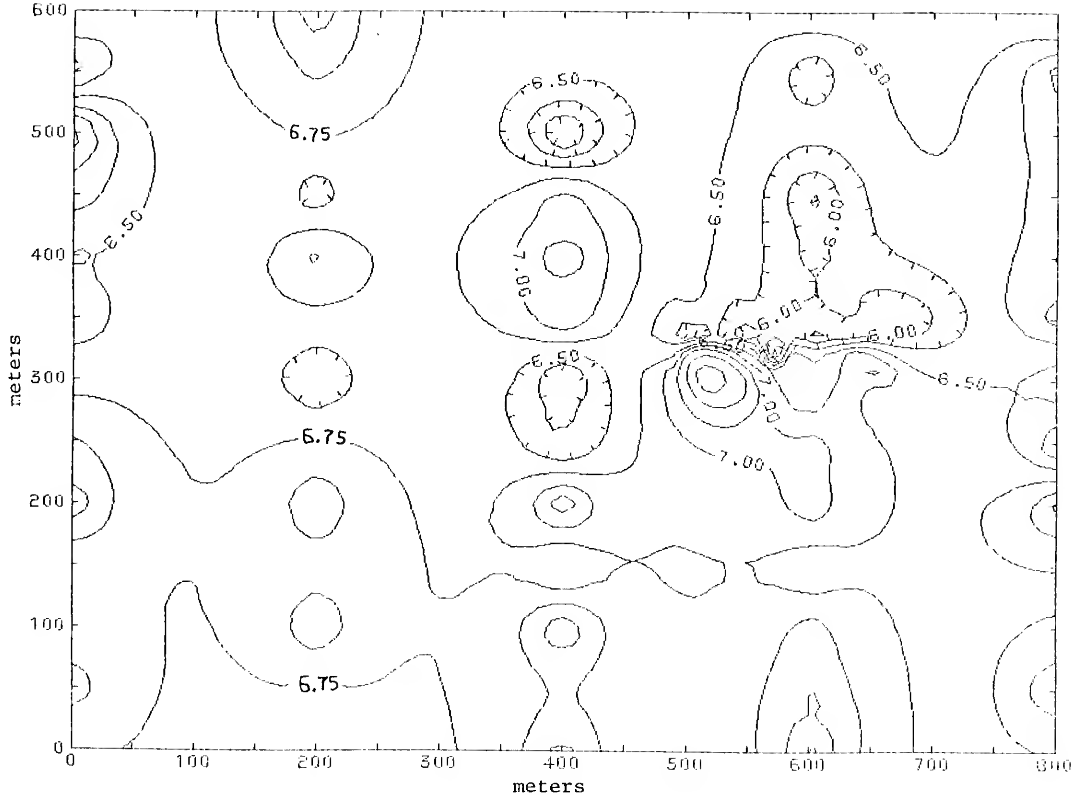


Fig. 23. Kriged H_2O-pH, large grid (increment is 0.25).

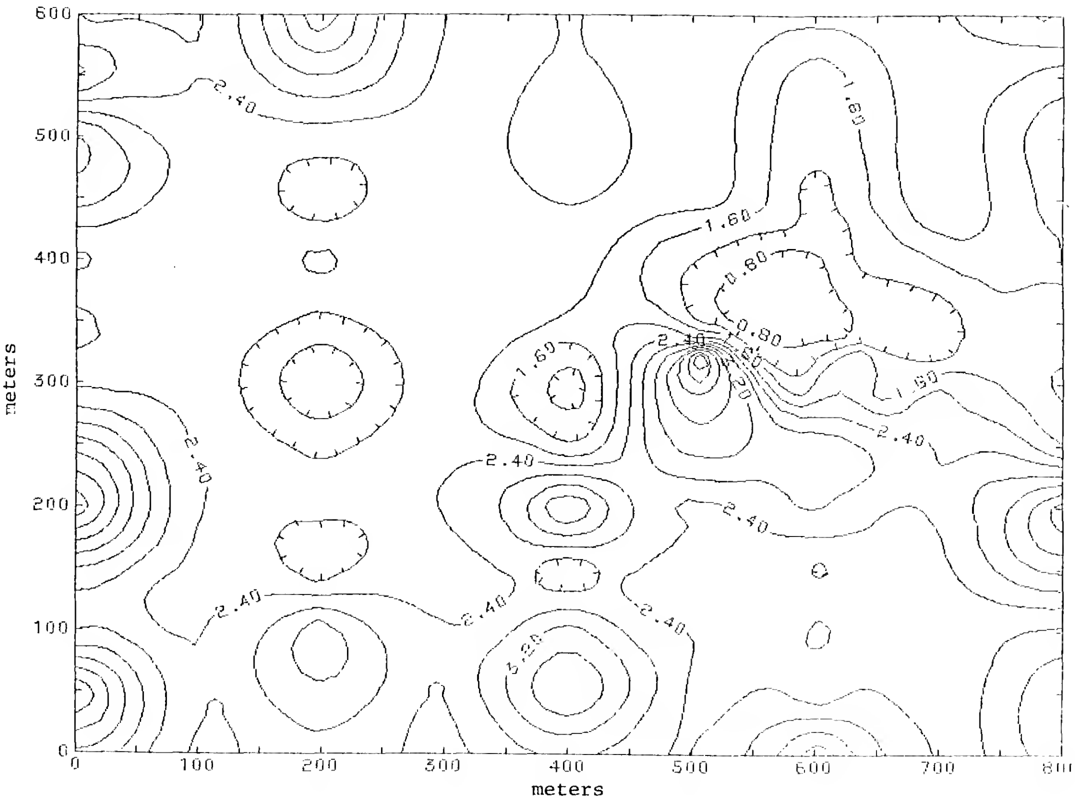


Fig. 24. Kriged extractable Mg, large grid (increment is 0.4 meq/100 g).

Additional insight into the placement of the contours was gained by examining the associated error maps. The contours of the error maps were somewhat similar to each other. All showed the medium grid and at least some of the individual sampling points in the large grid. The density of contours around the medium grid and other points was more a function of the range of each semi-variogram.

The sand (Fig. 25) and extractable K (Fig. 26) error maps were similar because both have very long ranges. Extractable Mg (Fig. 27), OC (Fig. 28), and extractable acidity (Fig. 29) error maps looked alike because these three parameters have the shortest ranges. The sampling scheme was vividly apparent in these maps, each sample location enclosed by a contour. It was even possible to locate the two small transects inside the medium grid by the small circles near its western edge.

The error map for elevation (Fig. 30) looked different from the others because there were only 155 samples instead of 204. The contours showed that elevation was not measured for any samples x=0 or x=800.

The small (Figs. 31-36) error maps turned out to be actual "enlargements" of corresponding portions of the large grid error maps. There were about 400 more Kriged points in the small map area compared with the same area on the large grid map. The only differences were cosmetic. The small error maps exhibited finer increments in contours than the large grid error maps.

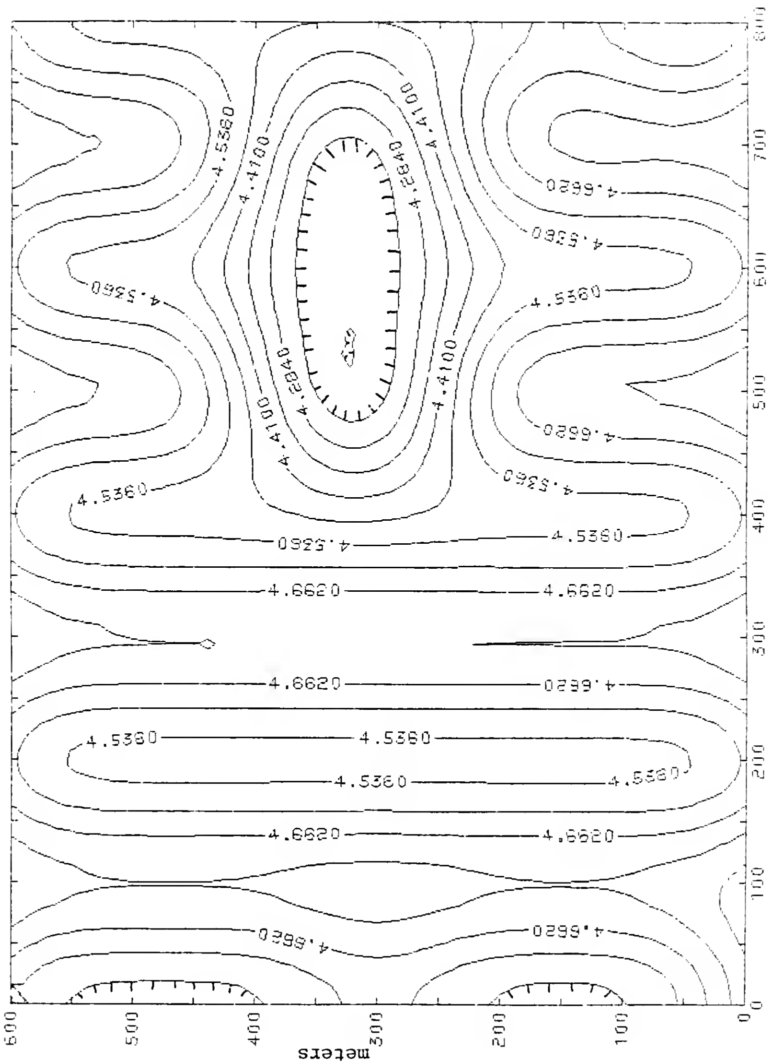


Fig. 25. Error of Kriged sand, large grid (increment is 0.063%).

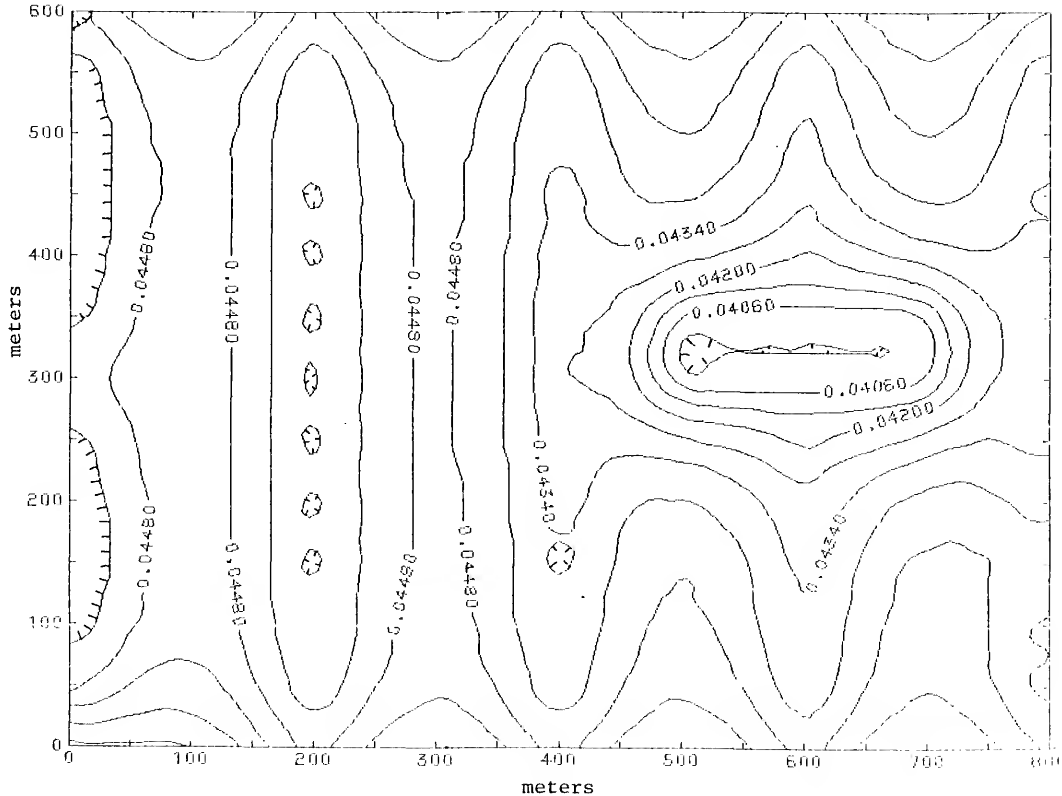


Fig. 26. Error of Kriged extractable K, large grid (increment is .0007 meq/100 g).

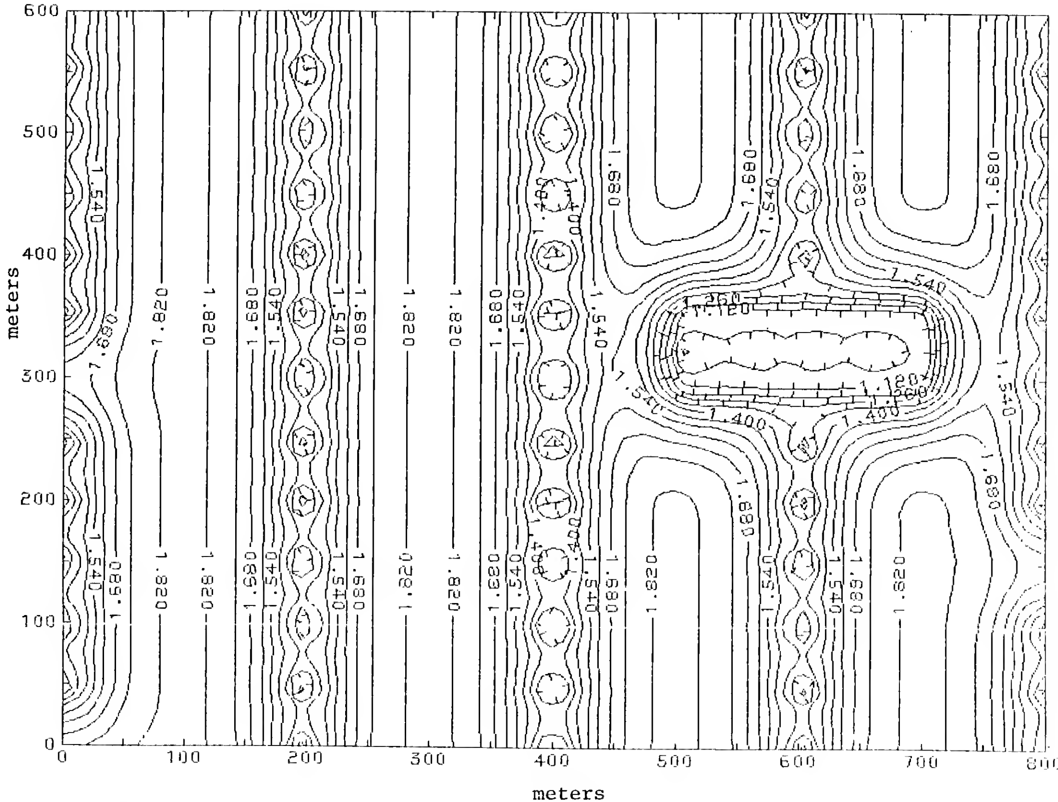


Fig. 27. Error of Kriged extractable Mg, large grid (increment is 0.07 meq/100 g).

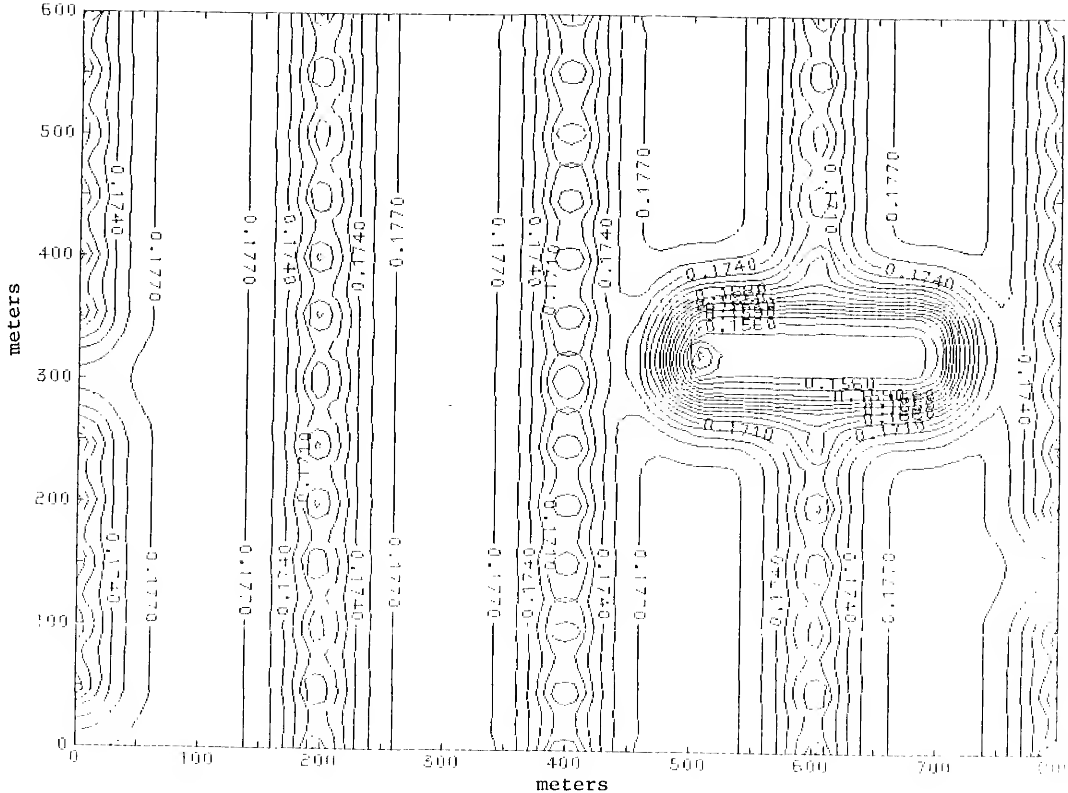


Fig. 28. Error of Kriged organic C, large grid (increment is .0015%).

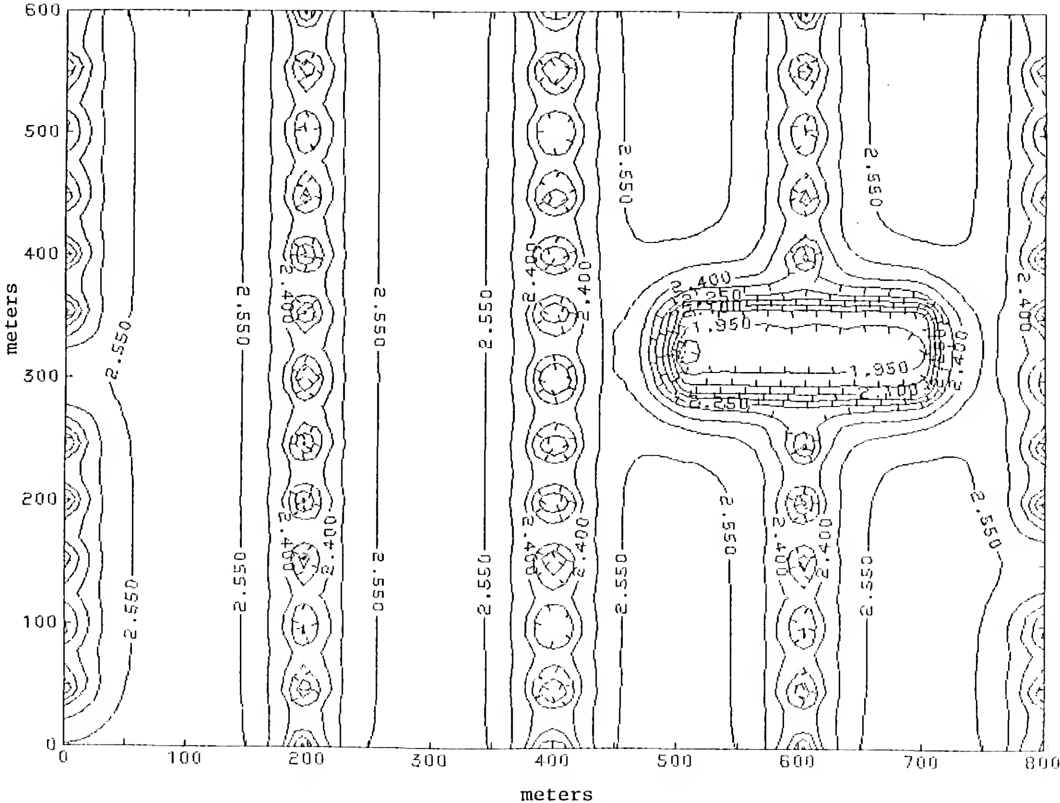


Fig. 29. Error of Kriged extractable acidity, large grid (increment is 0.075 meq/100 g).

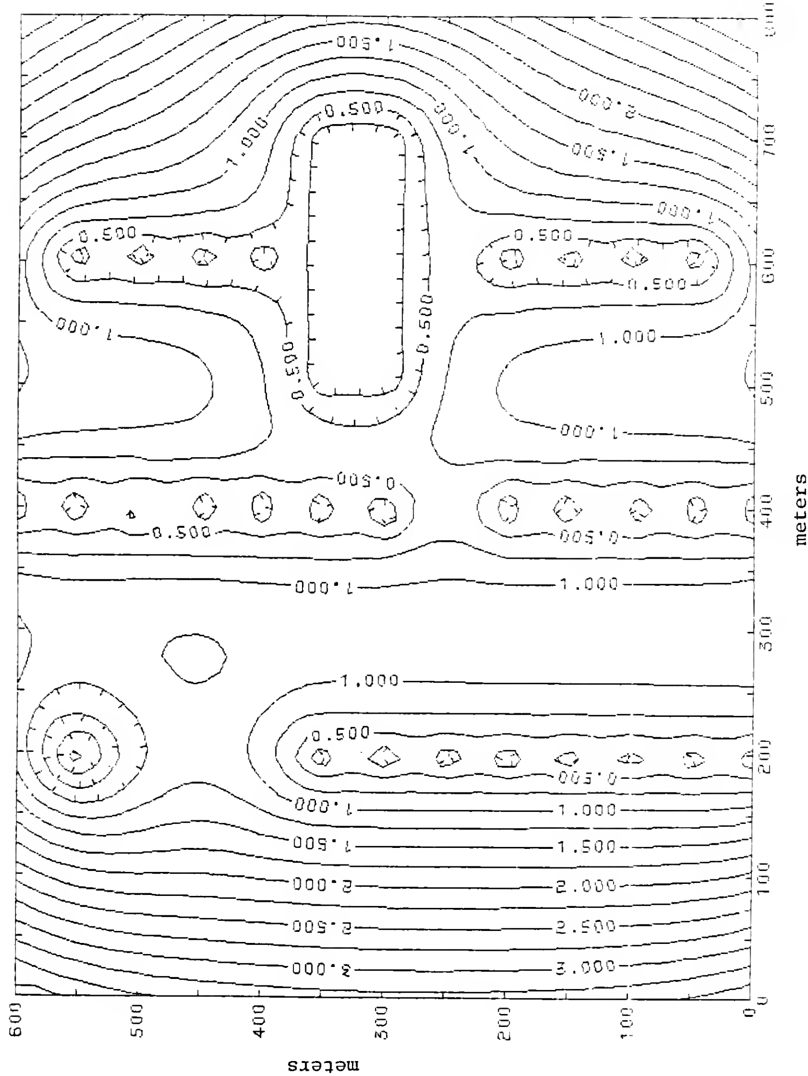


Fig. 30. Error of Kriged elevation, large grid (increment is 0.25 ft).

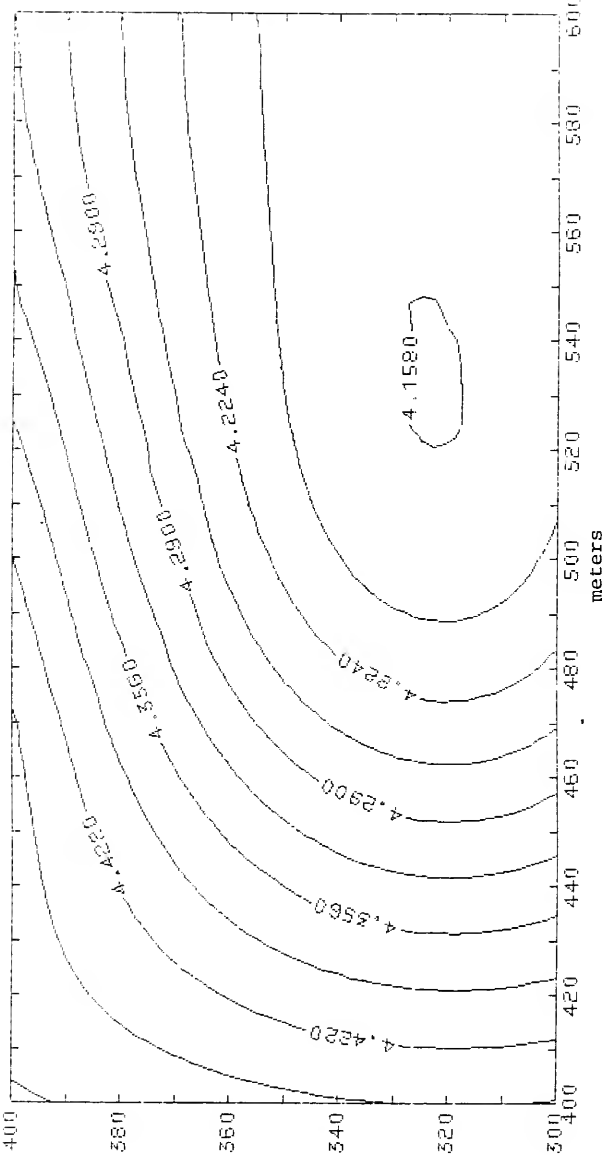


Fig. 31. Error of Kriged sand, small map (increment is 0.033%).

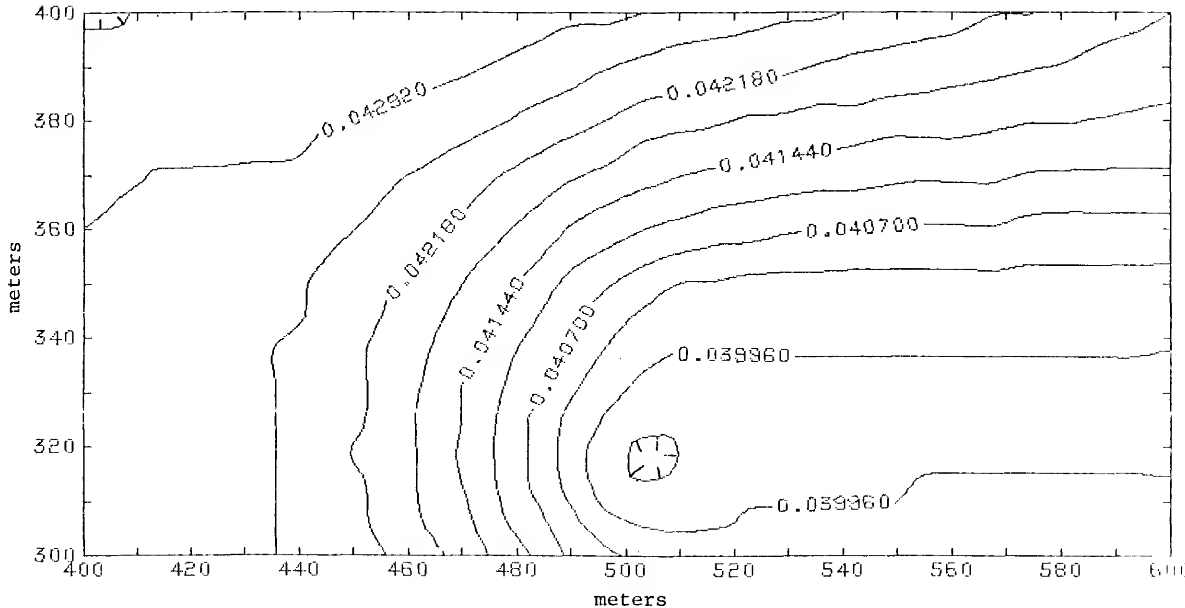


Fig. 32. Error of Kriged extractable K, small map (increment is .00037 meq/100 g).

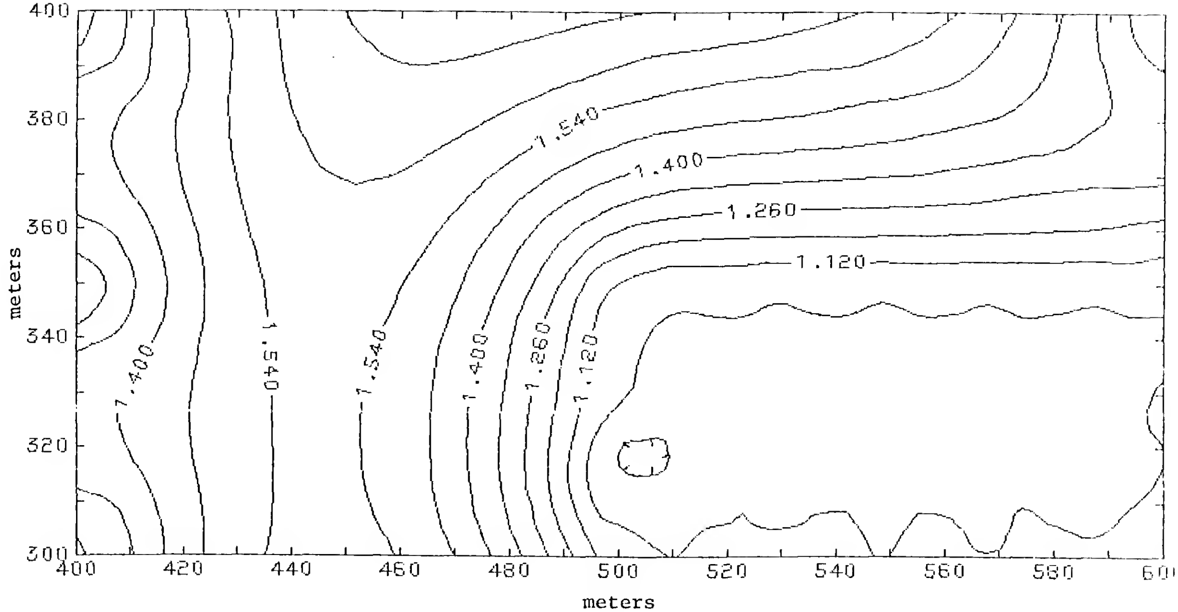


Fig. 33. Error of Kriged extractable Mg, small map (increment is 0.07 meq/100 g).

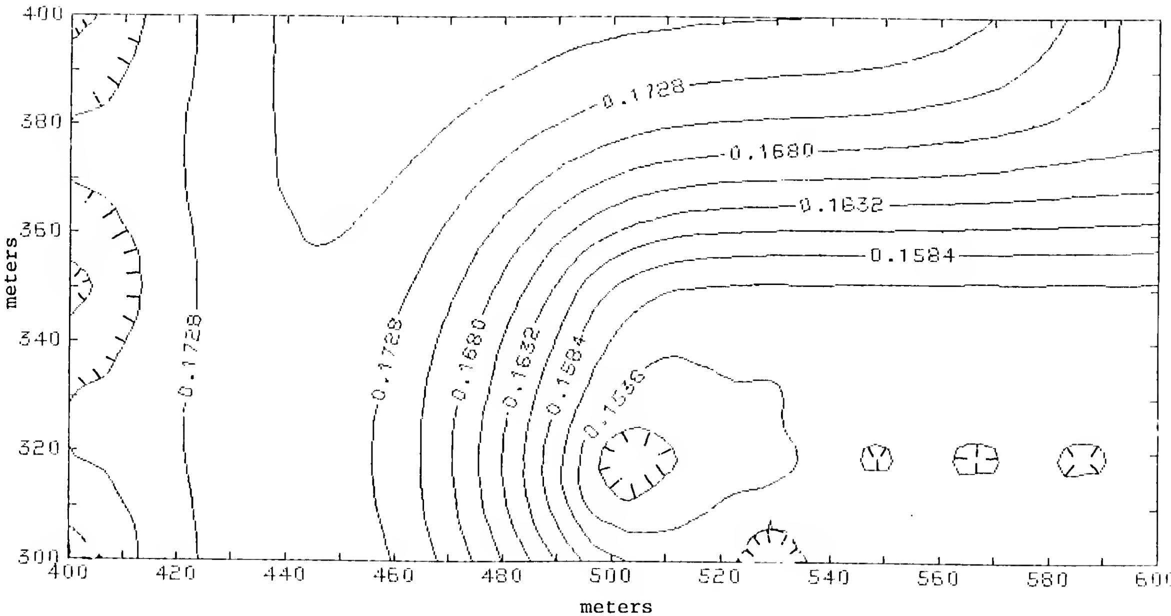


Fig. 34. Error of Kriged organic C, small map (increment is .0024%).

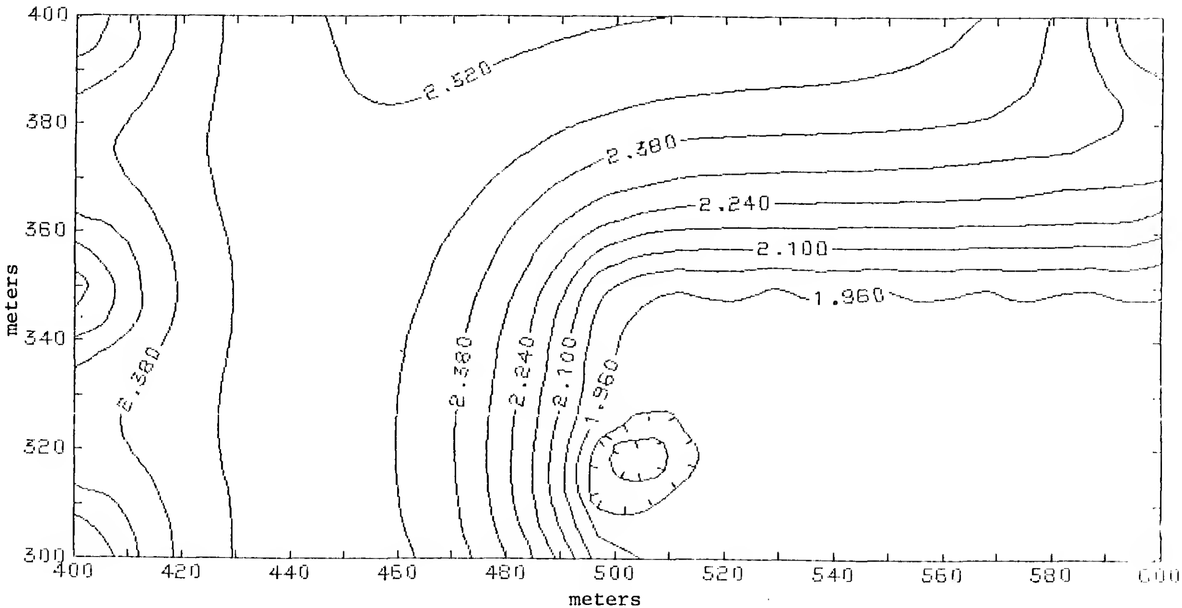


Fig. 35. Error of Kriged extractable acidity, small map (increment is 0.07 meq/100 g).

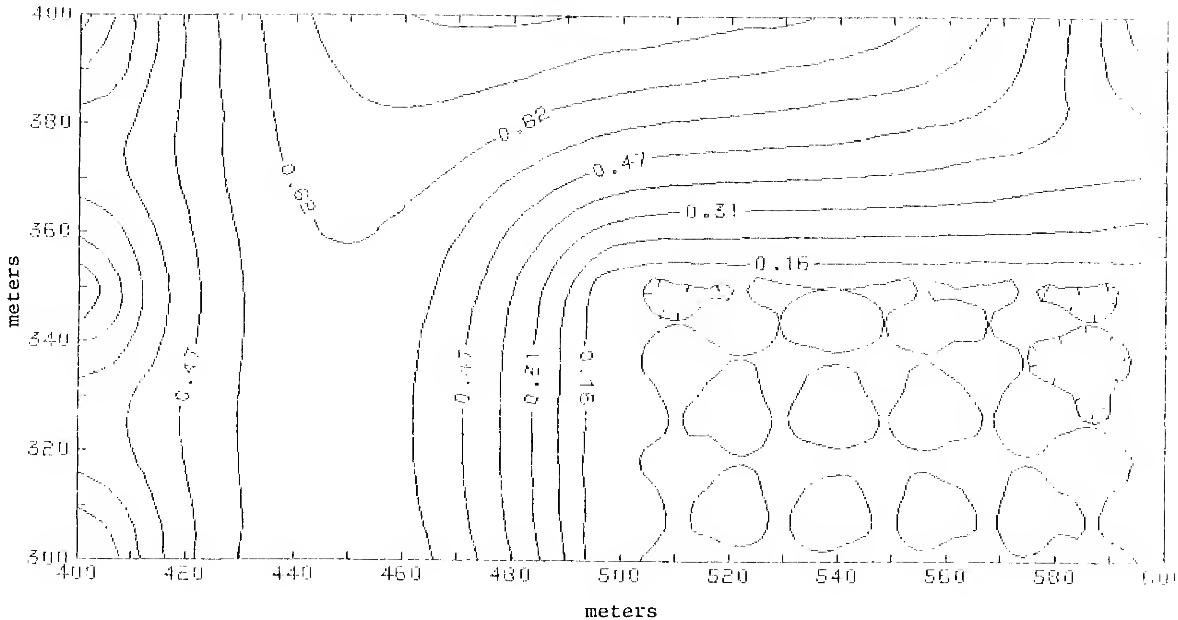


Fig. 36. Error of Kriged elevation, small map (increment is 0.078 ft).

In studying mapping accuracy and similarity of distribution of other soil parameters, one should refer to the plan view of the site with the sampling scheme superimposed (Fig. 11). Of the 60 points in the large grid, at least 37 were located away from a spoil island. At least 10 other samples probably also were not on spoil for two reasons. First of all, the superposition of the sampling scheme on the photo was an estimate at best, leaving some error for all points in any direction. Secondly, the photo was taken before filling of ST was complete so there was no way of knowing which or what portions of the spoil islands on the picture actually remained at the end of filling. Approximately 47 of 60 points were not on spoil islands which causes an extreme test of geostatistics in predicting the locations of the spoil islands throughout the field than would have been possible if more points had been on spoil islands.

Of all the maps, the map of sand content probably was the most accurate over the whole field (Fig. 37). The contours did not specifically define the individual spoil islands but showed general trends instead. The sand content depressions represented the lower sand content of the spoil relative to the ST. The elevated contour around (250,250) accurately represented the deposit of tailings in this area. Even though point (0,0) was not sampled, the contour depression in this area showed the presence of the spoil as

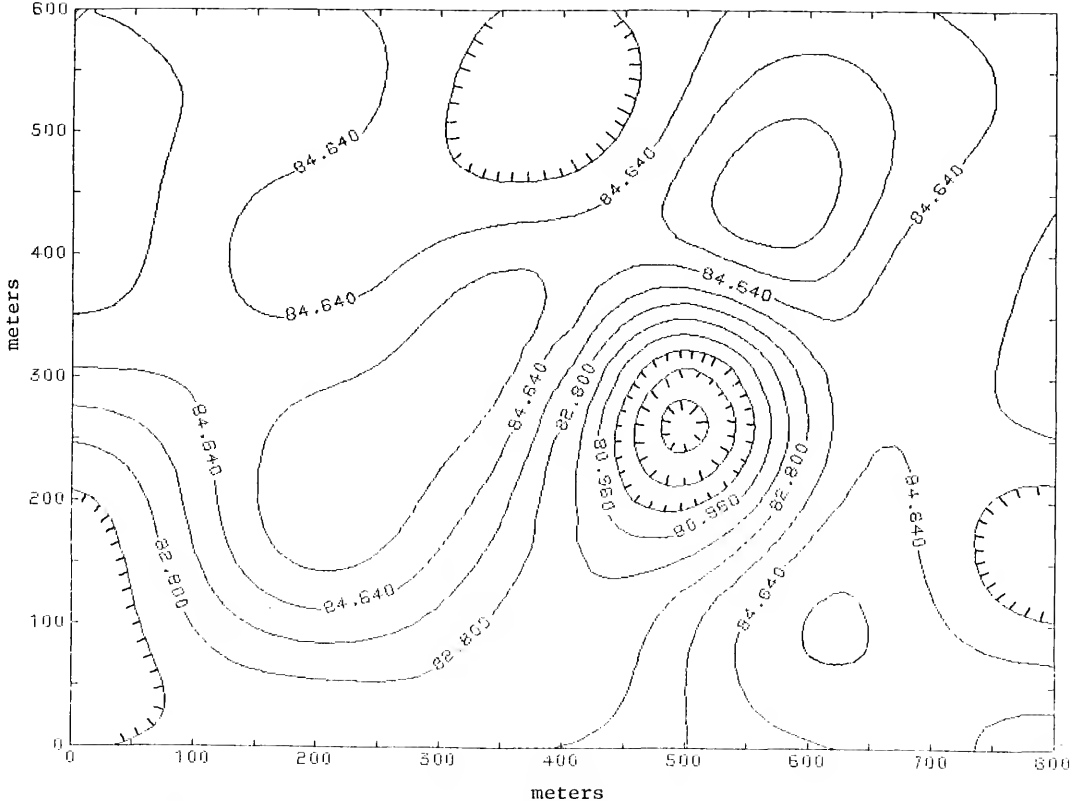


Fig. 37. Kriged sand, large grid (increment is 0.92%).

shown by the picture. The depression around (500,300) showed the presence of the spoil island in this area too.

According to the aerial photo, all the points on the eastern boundary, x=800, fall on spoil (Fig. 11). Since these points were actually measured, the spoil in this area must not have a lower sand content relative to the ST or to the spoil in other parts of the field. Otherwise, the whole side would have been identified as a depression. The elevated area around (550,450) completely missed the spoil island that was centered there. It appeared that the spoil island either was buried by the sand or, like the spoil on the eastern boundary, did not have a relatively low sand content.

Except for the extractable K, elevation, and sand content maps, the rest of the contour maps were confounded enough by the effects of the sampling scheme to make them only marginally useful. Considering the wide spacing of points in the large grid coupled with the "luck" of the scheme in missing most of the spoil islands, it would be unwise to expect the maps to be highly accurate.

Another test of the Kriging system (not included in the Skrivan and Karlinger program) was run to check for precision of the semi-variograms in estimating points in the field that were not used in the semi-variogram calculations. A north-south transect of 11 points spaced 50 m apart was located at x=500. Only two of these points were used in the semi-variogram calculation since they

corresponded to the north-west and south-west corners of the medium grid, but each point location was Kriged using the semi-variogram calculated for the other points. The estimated values were then correlated with the measured values. The parameters used for this test included H_2O-pH, KCl-pH, sand content, CEC, and OC content.

The r value for sand was most negative (-0.56) and the r value for KCl-pH was most positive (0.286) (Table 6). Neither of these values indicated a high level of correlation between the measured and Kriged values. Considering that a value representing 1 standard deviation was calculated for each estimated value, the interval consisting of the estimate +/- 1 standard deviation was compared to the measured values. In most cases, the estimated interval included the measured value as it should have. The interval of estimated sand contents failed to include the measured values 7 of 11 times. The intervals of CEC missed 4 of 11 times, OC and H_2O-pH missed 3 of 11 times, and KCl-pH missed 2 of 11 times.

This test indicated a poor correlation between the estimated sand values and the measured values, even though it appeared as if the sand map was the most accurate of the Kriged maps. The sand map may have looked most accurate because it showed the general trends of sand content across the field. The Kriging system was not, however, capable of identifying the boundaries of the spoil islands.

Table 6. Correlations of Kriged versus measured values for 11 points.

Variable	r
H_2O-pH	0.102
KCl-pH	0.286
Sand	-0.560
Cation Exchange Capacity	-0.284
Organic Carbon	0.240

Values at the same two locations (500,300) and (500,350) for each parameter were always outside of the estimated intervals. These locations corresponded with the western corners of the medium grid. Since the Kriging system assumed the locations of these two points were the same locations as the measured values, the error term was always approximately zero. The error term more realistically should have been at least as large as the standard deviation, which approximates the square root of the nugget.

The poor correlation between estimated and measured values probably resulted from a combination of short ranges relative to the distances between the estimated points and nearest measured neighbors (100 m) and the size of the nugget variance relative to the sill. The majority of the locations of the estimated points had two closest neighbors 100 m away, two more 110 m away, and two more 141 m away. These distances were all beyond the ranges or near the range limits for the parameters H_2O-pH, CEC, and OC.

Sand and KCl-pH had ranges greater than 200 m although the estimates of KCl-pH were more highly correlated with measured values than were the sand estimates. The sand nugget was much larger relative to the sand sill than was the KCl-pH nugget relative to the KCl-pH sill. The higher relative nugget of sand would result in a much greater random error of the estimated points around the values of the measured points.

Because of more closely spaced sampling pattern and larger scale, the small maps were much more useful in depicting the relationships between parameters and in showing which parameters were dependent on position relative to the spoil. The maps covered an area 200 m along x and 100 m along y and consisted of parts of the large sampling grid and parts of the medium grid. The medium grid fills the southeast quadrant of these larger scale maps from x=500 to 600 and y=300 to 350.

Inside the medium grid, one of the data sets that gave the most information was that on depth of spoil. From these measurements, the spoil islands were accurately identified, much more accurately than with the aerial photos alone. Also, these data allow for the different parameters to be correlated with position relative to the spoil islands.

According to the depth of spoil measurements, the medium grid touched two spoil islands on the south edge. One spoil island lies on the southwest corner and the other was located between x=610 and x=670 (Fig. 12).

Contours of individual parameters that follow the depth contours should indicate correlation of values with position relative to the spoil islands. Maps with contours similar to these may indicate some type of correlation between parameter types.

Overall, the small maps of CEC and extractable Mg were most similar (Figs. 38 and 39). Bos et al. (1984) reported extractable Ca and Mg values to be a good indicator of CEC

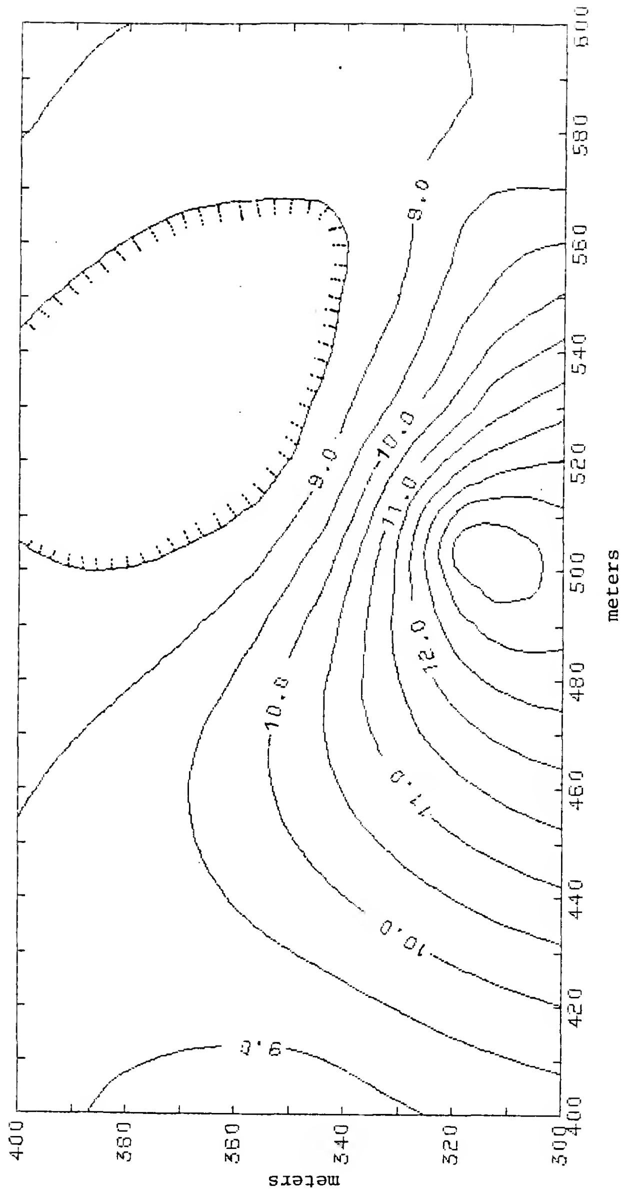


Fig. 38. Kriged CEC, small map (increment is 0.5 meq/100 g).

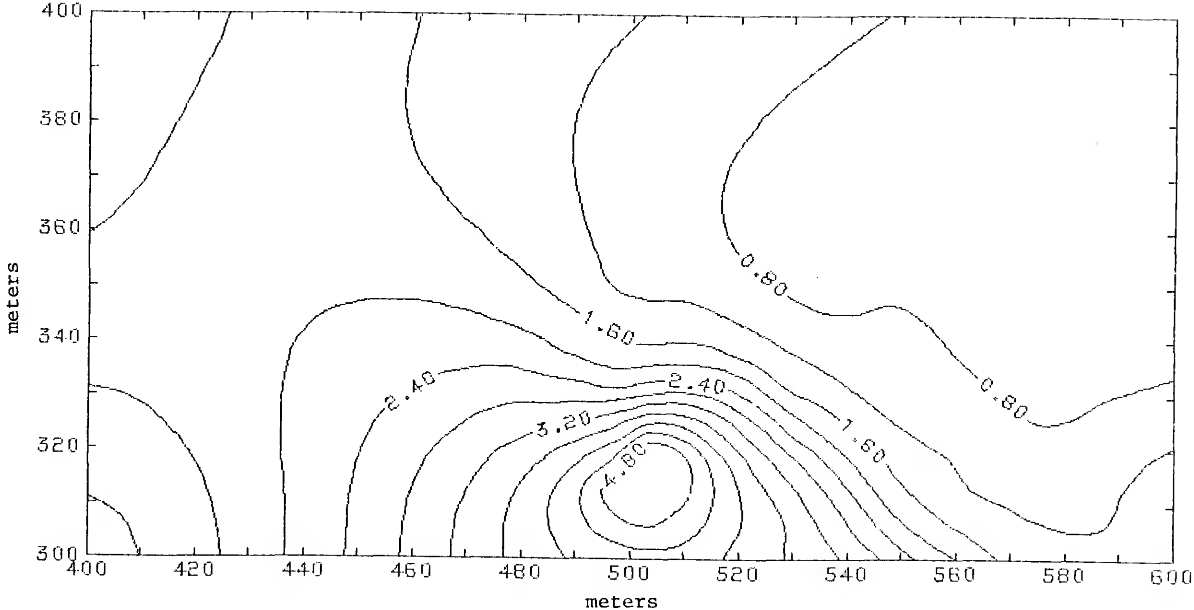


Fig. 39. Kriged extractable Mg, small map (increment is 0.4 meq/100 g).

since the quantities of these bases were so much higher than Na and K (two other bases added into CEC calculations). This would explain the similarity in contour shapes.

On a much more local level, contour lines circled the point (500,310) on the CEC, extractable Mg, K, and acidity and KCl-pH maps (Figs. 38-42). In each case, the contours, were attributed to the presence of relatively large quantities (about 50% of the sample volume) of yellow siltstone found in samples in this area.

The siltstone was soft, partially weathered, and according to qualitative X-ray diffraction analysis, contained predominantly quartz, dolomite, and apatite. Presence of this siltstone in the sample contributed to the higher extractable Mg and CEC values by releasing Mg and Ca from the dolomite to the ammonium acetate extractant and by having increased the silt and clay content of the samples as the rocks weathered in the field. Large quantities of the siltstone probably also lowered the extractable acidity and raised the KCl-pH to the levels found in these areas. The siltstone content may have indirectly affected K content by influencing the soil texture. The main source of K appears to be from fertilizer, but the finer texture of samples in this area would increase the exchange capacity, and therefore the K retention capacity, of the soil.

Comparison of Kriged and Non-Kriged Contour Maps

Contour maps were drawn of the 204 sand and OC data points without the additional 2000 Kriged points to compared

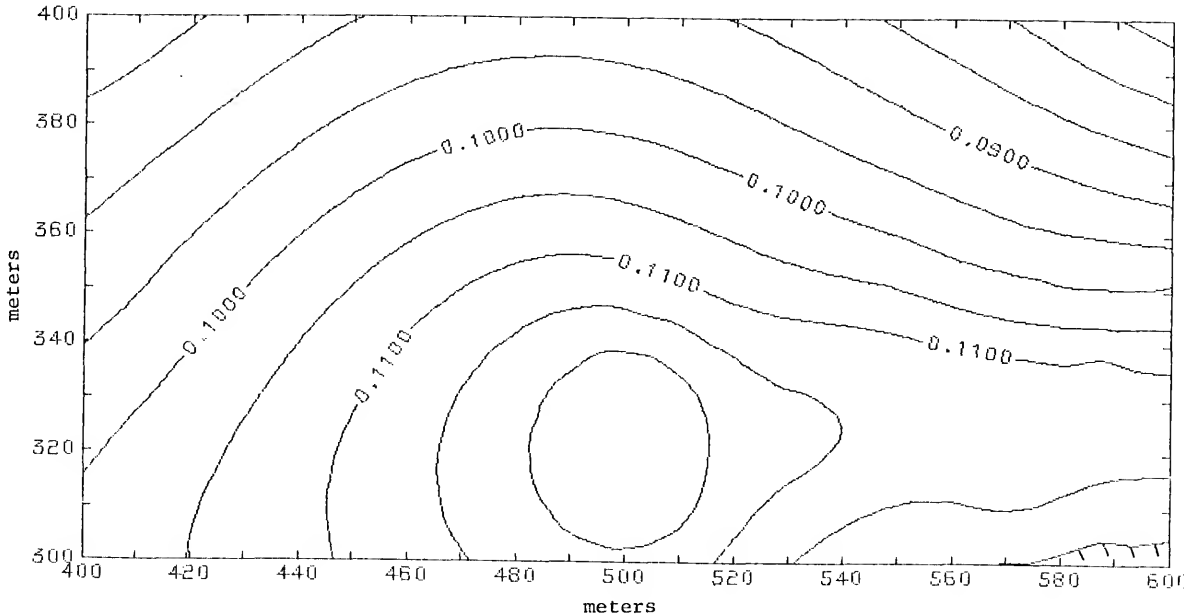


Fig. 40. Kriged extractable K, small map (increment is 0.005 meq/100 g).

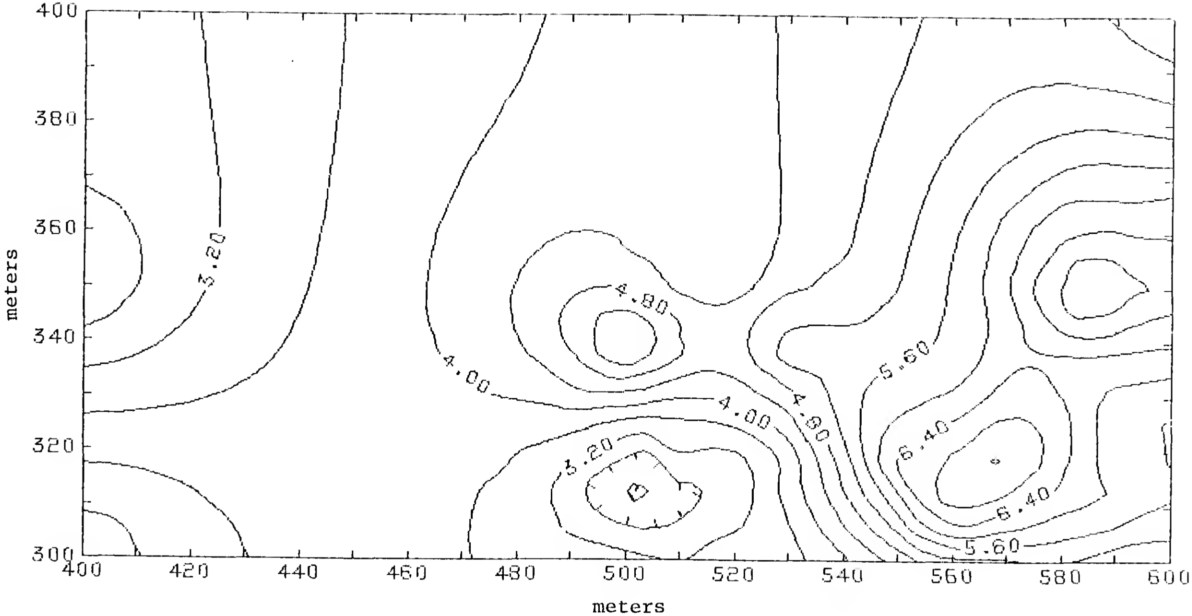


Fig. 41. Kriged extractable acidity, small map (increment is 0.4 meq/100 g).

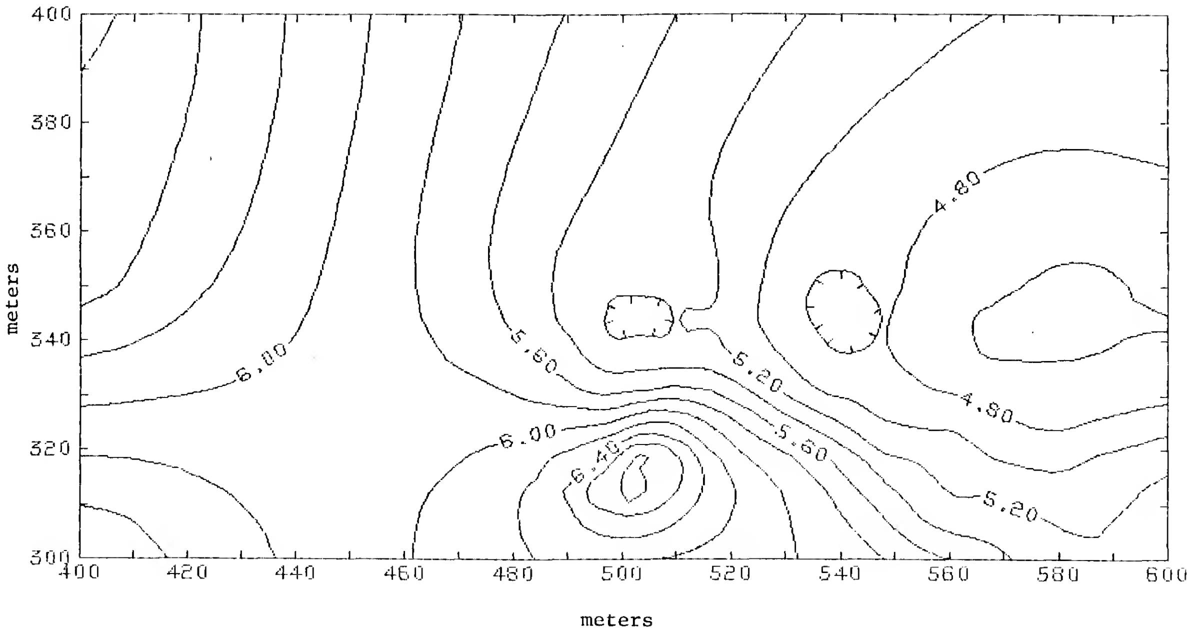


Fig. 42. Kriged KCl-pH, small map (increment is 0.2).

to the contour maps of the Kriged points (Figs. 21, 37, 43, and 44). If the non-Kriged maps were found to be as good as the Kriged maps, then it would be much more efficient (in economics and time) to contour without Kriging.

The most noticeable difference between the Kriged and non-Kriged maps was in the amount of smoothness exhibited by the contour lines. The Kriged maps were much smoother than the non-Kriged maps. The Kriging system tends to smooth out the data by not returning the highest or lowest values of the input data set during the estimation of the new points. All of the Kriged maps represented only the output of the Kriging program, without including the 204 input points. This also resulted in the non-Kriged maps exhibiting a wider range of values than the Kriged maps. The non-Kriged sand map exhibited a range of 66.5 to 91% while the Kriged map exhibited a range of 78.2 to 86.5%. The non-Kriged map of OC exhibited a range of 0.21 to 1.05% while the Kriged map showed a range of 0.29 to 0.6%.

There was no clear-cut decision as to which maps, the Kriged or the non-Kriged, were better. Considering that the sampling scheme was not capable of adequately describing the spoil islands in the field it may have been better at least economically to have contoured the maps using only the measured values instead of the Kriged points. This does not mean that the non-Kriged maps are better, just less expensive. If Kriging is considered as the best interpolating procedure, a sampling scheme inadequate for

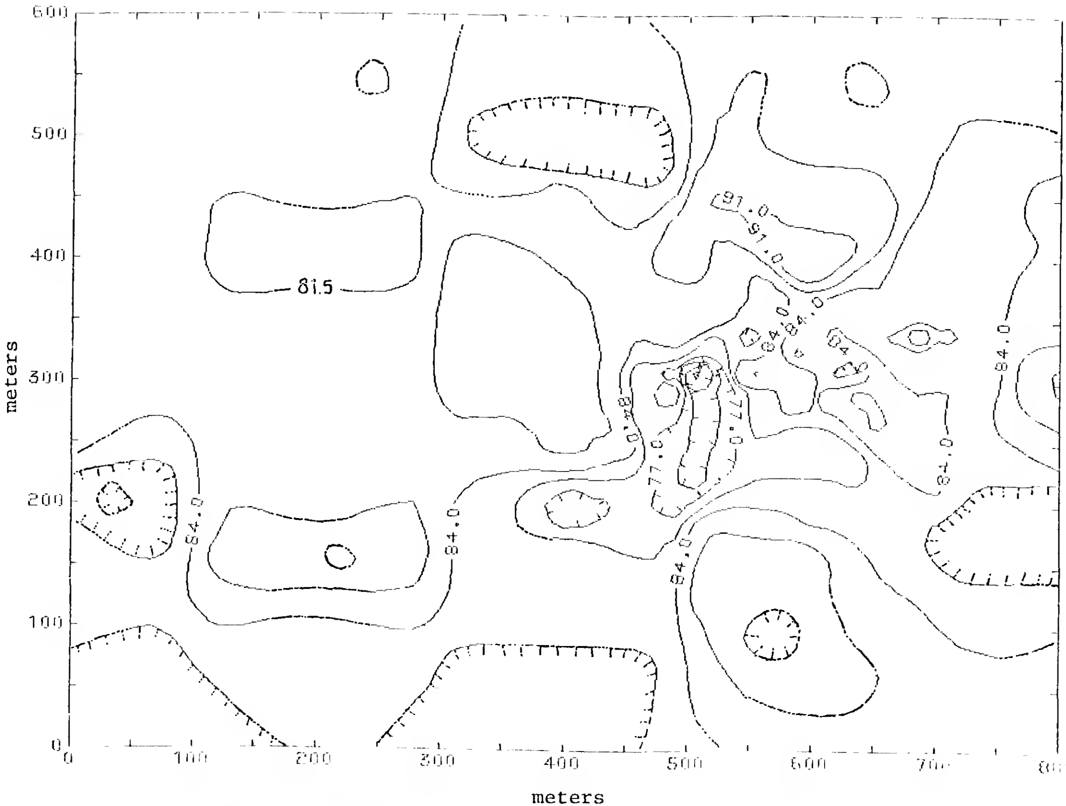


Fig. 43. Non-Kriged sand, large grid (increment is 3.5%).

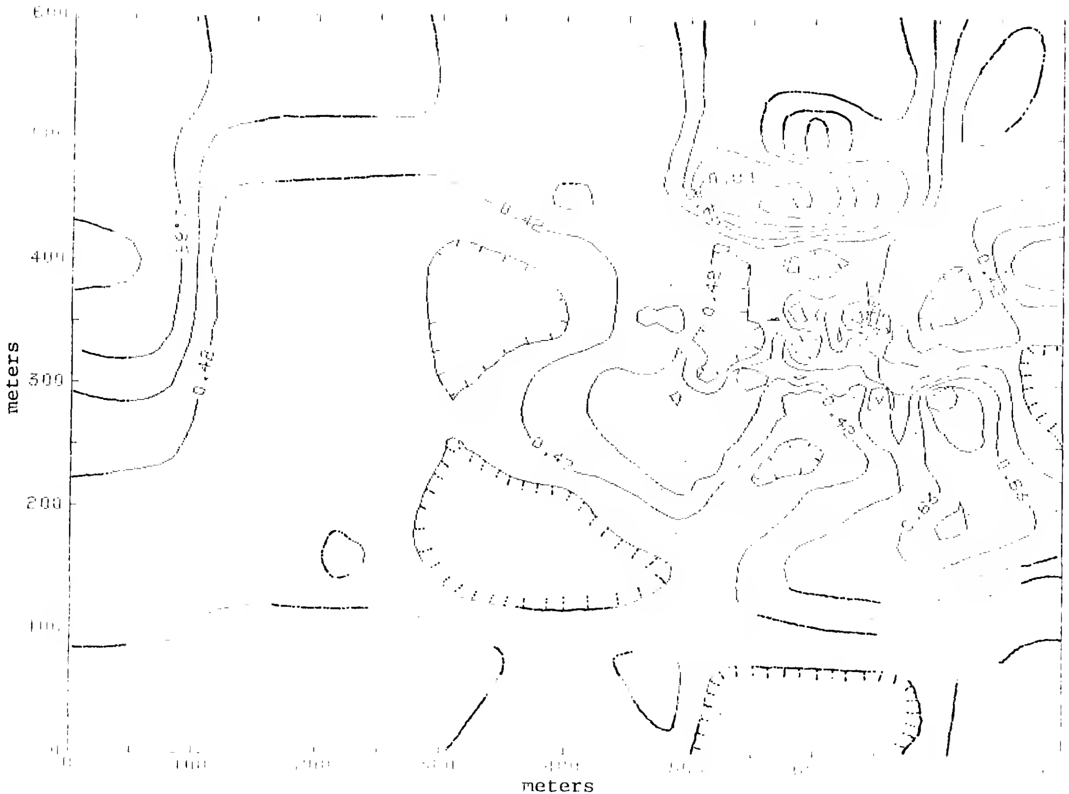


Fig. 44. Non-Kriged organic C, large grid (increment is 0.105%).

Kriging will be inadequate for the other interpolating procedures.

If, on the other hand, a 100 x 100 m sampling scheme had been used, the Kriging system might have resulted in better maps. More of the spoil islands would have been sampled giving a much better representation of the spoil and the sand tailings. In addition, the sample points would have been close enough so that, during interpolation, the part of the semi-variograms closer to the origin would have been used more often, resulting in less error for the estimated points.

Applicability of Standard Soil Analytical Procedures for Minesoils

The EPA publication, "Field and Laboratory Methods Applicable to Overburdens and Minesoils" (Sobek et al., 1978), states that some standard methods and procedures are not applicable to coal mine OB analysis. The authors, in fact, recommend different procedures for different OB characteristics. The same situation may apply to phosphate minesoils and OB. From observations in this study, it appears that some procedures should be altered or even replaced by other procedures to get more accurate results.

Bos et al. (1984) showed extractable Ca and Mg values to be the most important bases in CEC determination. The greater the percentage of Ca and Mg solubilized from dolomite rather than replaced on exchange sites, the greater will be the error in CEC determination by sum of cations.

It is suggested that a Na or NH_4 saturation method of CEC determination would be more favorable.

Another laboratory method used in this study, the pipette method of particle size distribution, may have to be altered slightly for greater precision and accuracy in measurements. The abundance of yellow siltstone in some samples may have decreased precision as well as accuracy. Overnight soaking coupled with mechanical mixing was enough to disperse the soil aggregates but may not have been adequate to slake all of the small siltstone particles. A 2-3 day soaking and/or a longer mixing time may help to disperse the softer siltstone aggregates more consistently.

The siltstone was always soft enough to be scratched by a knife and sometimes soft enough to be crushed between the fingers. The softer type was just more weathered than the harder type and was usually found surrounding the harder type. The soft siltstone readily slaked but the harder did not. Different rates of slaking in the sand or silt size fraction during particle size distribution analysis will alter the measurements somewhat. The potential for a problem to exist was observed during the extractable acidity procedure. When the 25 g samples were mixed with 100 ml $BaCl_2$-TEA, the volume of the total solution occupied by the soil was very small, about 1/3. After shaking and then settling overnight, the samples containing abundant siltstone dispersed enough to fill more than 2/3 of the

total volume of suspension. Samples without siltstone showed no soil dispersion.

CONCLUSIONS AND PRACTICAL APPLICATIONS OF RESULTS

Phosphate minesoils are different from native soils in several ways. First, except for incipient A horizon formation, phosphate minesoils younger than 10 years of age generally do not exhibit horizonation. They do exhibit layering, but the layers in a minesoil are a result of the mechanical mixing of spoil during mining and reclamation rather than resulting from soil forming processes. The presence of layers of such varying characteristics limits the usefulness of the standard soil classification procedures.

Another difference between native soils and minesoils may be site specific, without general application. On this particular site in Polk County, the minesoil in some parts of the field contained significant amounts of weatherable rocks and minerals (yellow siltstone, dolomite, and apatite). A reclaimed site planted to Eucalyptus, 12 miles away, also had significant amounts of weatherable minerals, but not the same kinds of minerals. The Eucalyptus site apparently had little of the dolomite but enough of the leach zone material (aluminum phosphates) to cause Al toxicity symptoms in the trees. The native soils in the area before mining were predominantly sandy and siliceous.

It was fortunate that the location of the medium grid coincided with the location of a spoil island. Surface and subsurface samples from this grid exhibited some interesting trends. These trends indicated that significant amounts of leaching of nutrients apparently occurred between the end of mining and the beginning of reclamation. Values of all parameters studied, except for extractable K and elevation, depended on location relative to this spoil island. This same dependence could not be examined over the rest of the field due to the small number of sample locations.

Before a comparison of native and minesoil variability can be initiated, much fine tuning of methods would be required. This is immediately apparent when looking at the lack of success in the contour mapping procedures used for the whole field.

The combination of relatively large sizes of the nugget variances with the long semi-variogram ranges contributed to the minimal mapping success. The distance between sampling points in the large grid was about twice as long as the ranges of variables, which minimized the usefulness of Kriging.

Of all the different Kriging variants, the lognormal variant may have been most useful in addition to the punctual Kriging used here. Lognormal Kriging might have resulted in better maps of elevation and sand (two populations suspected of being lognormally distributed). A range and sill might have been produced in the semi-variogram if

the transformed data had been used instead of the nontransformed.

Block Kriging would not have been useful since its main benefit is to smooth out discontinuities. All of the maps appeared to be overly smoothed because of the effects of short ranges and long distances between many of the points. The spoil islands would represent blocks much smaller than the 200x 50 m grid covering the field.

Universal Kriging was not very useful since elevation was the only data set exhibiting a trend. The Skrivan and Karlinger program is a universal Kriging program but the documentation needed to properly determine drift was lacking, so the full capability of the program was not used.

Disjunctive Kriging might have been useful, since none of the populations were normally distributed. It is not known whether the computational costs necessary to handle the transformations would have been worth the expected increase in mapping precision.

Optimally, the nugget variance should only consist of the within-sample variance. In this case it also consisted of variance due to experimental error and some positional variance that was not adequately removed by the sampling scheme. The sampling scheme was found to be inadequate in representing the relationship of spoil and ST in the field.

The original grid (126 pts), however, was designed only to identify the spatial variability of the spoil while trying to eliminate the possible interactions caused by

ST. The objective was satisfied by the long rows of points parallel to the run of the spoil. The results of this scheme, though, indicated that the interactions of the spoil and ST (regularly increasing or decreasing values) were more important in identifying the field spatial variability than the variablity of the spoil alone. The attempts to satisfy this new objective (identifying the field spatial variability) were found to be inadequate.

It is important to set up a sampling scheme with equal numbers of points spaced at short, medium, and long lag distances to fully identify the nugget, range, and sill of the semi-variograms and to ensure equal representation across the field. This proposed sampling scheme might have resulted in entirely new semi-variograms, probably with smaller ranges and nuggets. Accuracy in mapping might have increased due to a more even spacing of measured points throughout the field.

Experimental error may be decreased by altering procedures (as with particle size distribution analysis) or even choosing more applicable procedures (as with CEC). By reducing the variance due to laboratory error and due to position, the true nugget (non-positional variability) would be estimated better, allowing for more accurate mapping.

In a more practical sense, the semi-variogram information can be used to help a farmer or citrus grower optimally evaluate soil fertility. The same system of 200 points that a researcher might put out would also be optimum

for the farmer/grower, but in all likelihood 20 samples would be a more realistic number to be taken.

The best method of setting out the points is to coordinate the sampling scheme with an aerial photo taken just prior to final bulldozing of the spoil islands. About one third of the points should be located on top of the spoil islands, 1/3 located away from the spoil, and 1/3 located between the two. This will ensure that the widest range of materials will be sampled, from ST to spoil.

If the photograph is not available, then a different scheme would be appropriate. The goal would be to maximize the chances of locating some samples on the spoil islands while keeping the points far enough away to be independent.

The ideal situation is first to determine the total number of samples to be analyzed, considering availability of time and money, and to divide that number by 3. Each subset would be used as a different sized sampling scheme to be placed in the field depending on semi-variogram analysis.

The first scheme used would consist of a grid of the most widely spaced points, covering the whole field. After analyzing the samples and calculating the semi-variograms from the first grid, the spacing of the second 1/3 of points would be determined. Some possible outcomes of the first analysis affecting the design of the second grid may be (i) the nuggets are relatively large, (ii) some pure nuggets exist, (iii) the ranges are relatively large, or (iv) OB islands were too infrequently sampled. Each of

these situations can be addressed by designing the proper placement of the second set of points.

The second set of points can be grouped over a particular part of the field or can be spaced at smaller intervals around points in the larger grid. Analysis of semi-variograms calculated from both old and new data may show that the initial problems have been solved or possibly that new problems have been created. Either way, the semi-variograms can be used to guide the placement of the final 1/3 of the points in the field. By basing the design of future sampling schemes on analysis of semi-variograms of existing data, excessive and possibly unnecessary variability within the data may also be minimized.

APPENDIX A
MODIFIED PROFILE DESCRIPTIONS OF MINESOILS AT FORT MEADE AND PAYNE CREEK SITE

PROFILE OF OB-CAPPED ST AT FORT GREEN

As described by G. Gensheimer and J. Bos, 27 May 82.

Depth (cm)	Description
0-16.5	Grayish brown (10YR 5/2) loamy sand; granular; very friable; few medium prominant red (2.5YR 4/6) rock mottles; abrupt smooth boundary.
16.5-28	Gray (10YR 5/1) loamy sand; granular; friable; few medium prominant rock mottles; common gray (N 5/0) clay lenses; common black (N 2/0) organic lenses; abrupt broken boundary.
28-38	Light brownish gray (10YR 6/2) loamy sand; massive; firm to very firm; few medium prominant yellowish red (5YR 5/8) rock mottles; abrupt smooth boundary.
38-60	Light gray (10YR 7/1) sand tailings.

PROFILE 1 PAYNE CREEK SITE

Described by G. Gensheimer and J. Bos, 27 May 82.
Approximate years since reclamation: 15.
Located in an erosion gully S15, T32S, R24E, Polk County, Florida.

LEFT SIDE OF PROFILE 1 M APART RIGHT SIDE OF PROFILE

Depth(cm)	Description	Depth(cm)	Description
0-18	Brown (10YR 5/3) sand	0-11.5	Dark grayish brown (10YR 4/2) sand
18-56	Light gray (10YR 7/2) sand with very pale brown (10YR 7/3) sand	11.5-43	Light gray (10YR 7/2) sand with pale brown (10YR 6/3) sand
56-94	Dark brown (7.5YR 3/2) sand with light gray (10YR 7/2) sand and pale yellow (2.5Y 7/4) sand; few distinct brownish yellow (10YR 6/8) rock mottles	43-77.5	Dark brown (10YR 3/3) sand with light gray (10YR 7/2) sand
		77.5-109	Light gray (2.5Y 7/2) sand with pale brown (10YR 6/3) sand; few prominant brownish yellow (10YR 6/8) rock mottles
94-135	Light gray (2.5Y 7/2) sand; few distinct brownish yellow (10YR 6/8) rock mottles	109-117	Black (7.5YR 2/0) sand with light gray (2.5Y 7/2) sand
135-152	Light gray (10YR 7/2) sand; few prominant yellow (10YR 7/6) rock mottles	117-152	Light gray (10YR 7/2) loamy sand; few prominant yellow (10YR 7/6) rock mottles

Remarks: Soil was structureless (massive) throughout the profile. Several roots were found along cracks in the sand down to 154 cm. The rock mottles are probbly remnants of well-weathered iron concentrations or iron-cemented sands. Colors are variable; listed colors are either the most common colors or colors that span the range.

PROFILE 2

Described by G. Gensheimer and J. Bos 27 May 82.
Approximate years since reclamation: 15.
Located in an erosion gully S15, T32S, R24E, 10 m closer to the lake than profile 1.

LEFT SIDE OF PROFILE		1 M APART	RIGHT SIDE OF PROFILE
Depth(cm)	Description	Depth(cm)	Description
0-18	Brown (10YR 5/3) sand	0-10	same
18-135	Brown (10YR 5/3) sand; few prominant yellowish brown (10YR 5/8) rock mottles	10-66	same
135-183	Dark yellowish brown (10YR 4/4) sand	66-75	same
183-188	Light gray (2.5Y 7/2) sand with olive yellow (2.5Y 6/8) sand and dark yellowish brown (10YR 4/4) sand; many prominant light gray (5Y 7/1) clay lenses	75-130	same
		130-165	Light gray (10YR 7/2) sand
		165-173	Black (5YR 2.5/1) sand with dark brown (7.5YR 3/2) sand
		173-188	Light gray (2.5Y 7.2) sand; common black (5YR 2.5/1) organic lenses; many light gray (5Y 7/1) clay lenses; few prominant brownish yellow (10YR 6/8) rock mottles

Remarks: Clay lenses in lower layers were abundant enough to cause the overall texture to be finer than sandy clay loam. Rock mottles are probably well-weathered remnants of iron concretions or iron-cemented sands. Colors are variable; listed colors are either the most common colors or colors that span the range.

PROFILE 3, PAYNE CREEK SITE

Described by G. Gensheimer and J. Bos, 27 May 82.
Approximate years since reclamation: 15.

Depth (cm)	Description
0-193	Brown (10YR 5/3) and very dark grayish brown (10YR 3/2) sand; common horizontal lenses of white (2.5Y 8/2) silt loam, silty clay loam, and clay less than 2.5 cm thick and up to 18 cm long, comprising about 5% of profile; few to common cobblestones and pebbles, including some pebble-size iron concretions of reddish yellow (7.5YR 6/8), with yellowish brown (10YR 5/6) interiors; soil below 135 cm depth more compact than material above.

APPENDIX B
DIRECTION INDEPENDENT SEMI-VARIOGRAMS OF SAND, ORGANIC C, AND EXTRACTABLE K

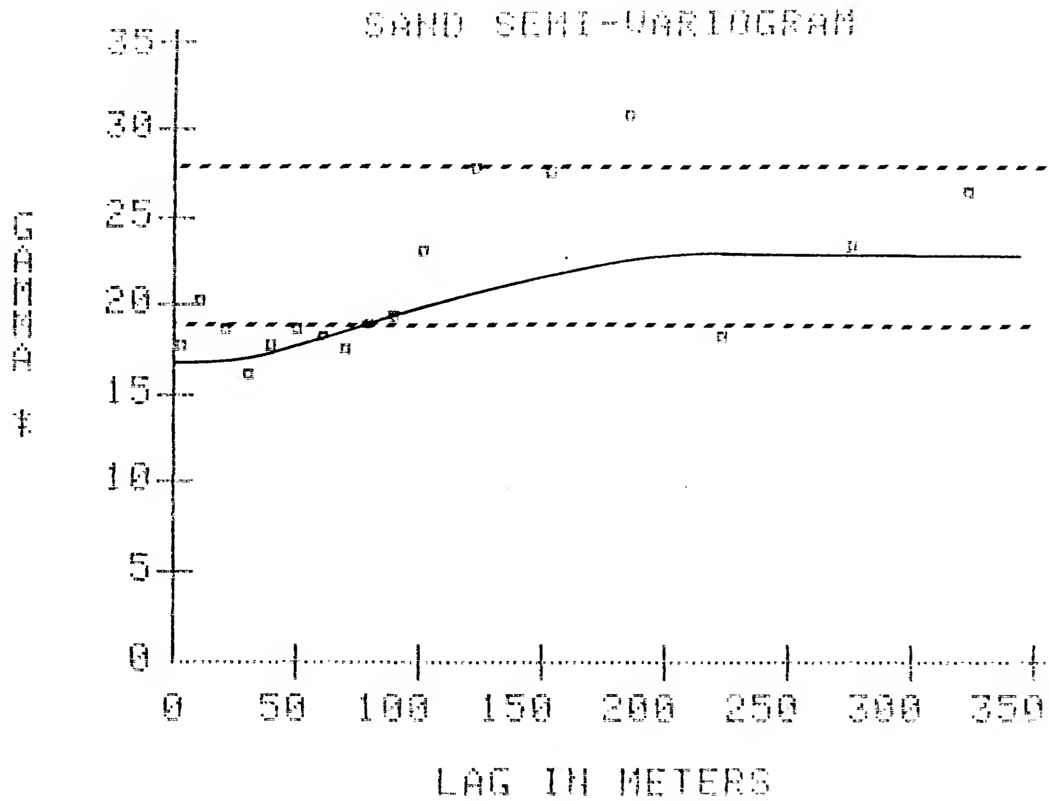


Fig. B-1. Sand direction-independent semi-variogram calculated from all 204 points.

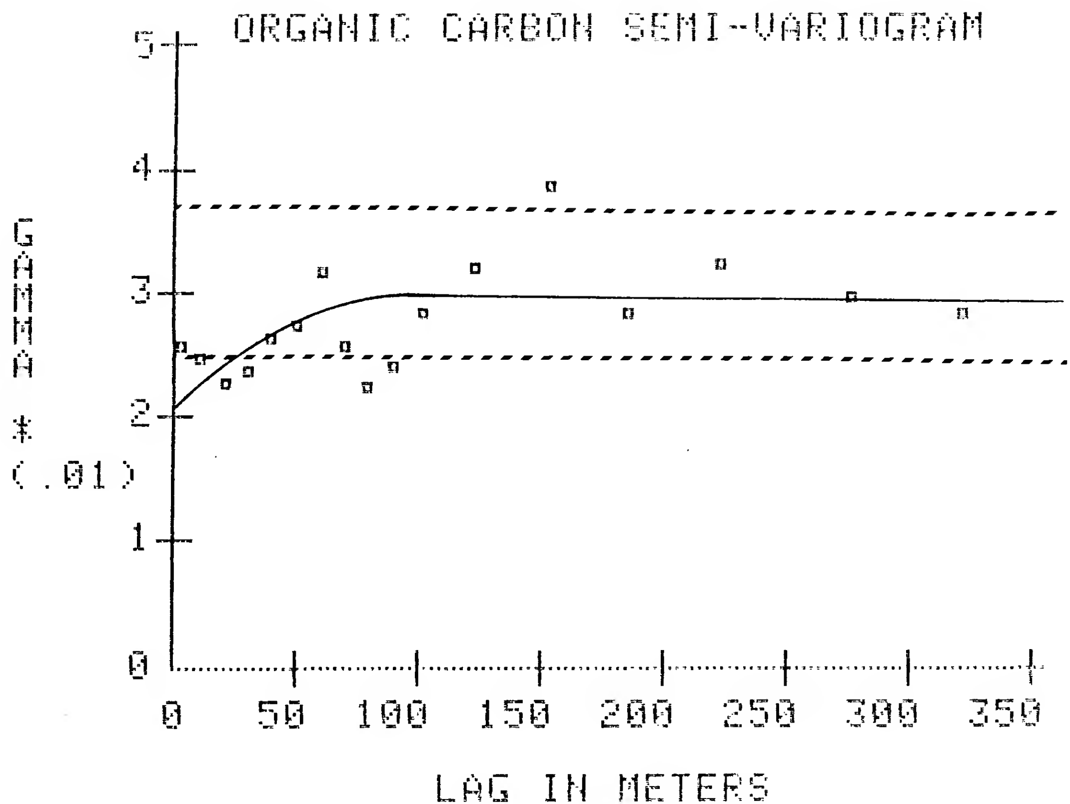


Fig. B-2. Organic C direction-independent semi-variogram calculated from all 204 points.

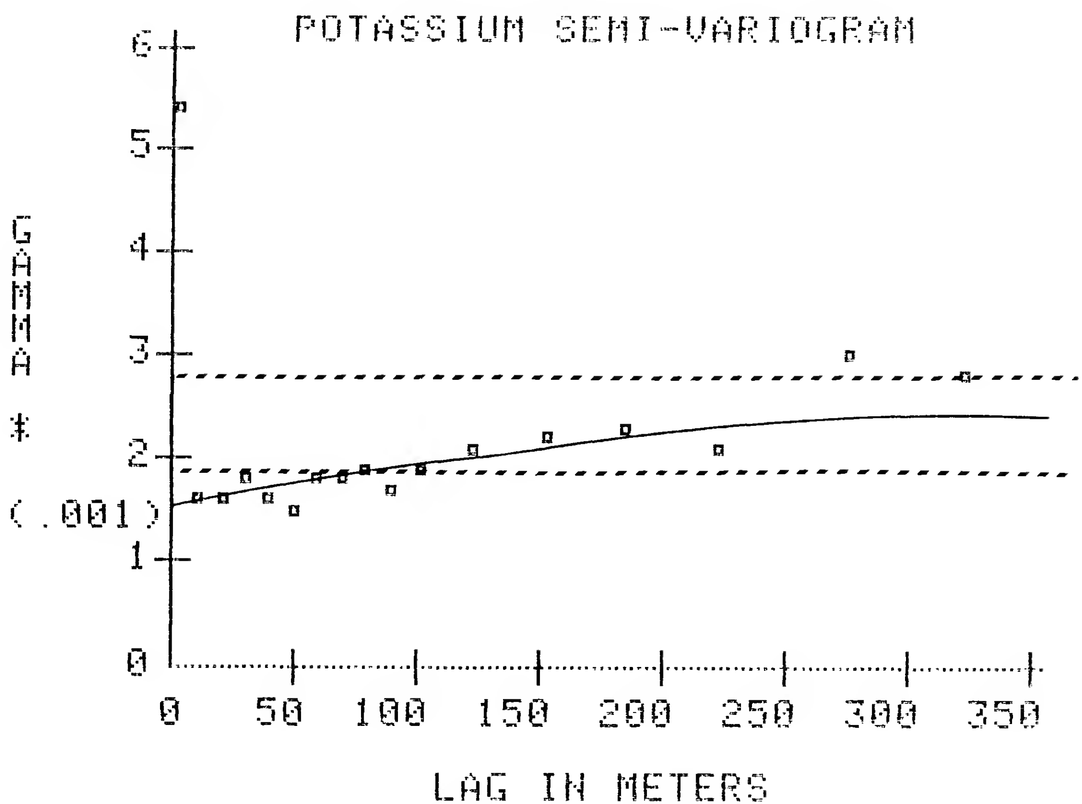


Fig. B-3. Extractable K direction-independent semi-variogram calculated from all 204 points.

APPENDIX C
MISCELLANEOUS CONTOUR MAPS OF PARAMETER VALUES AND ASSOCIATED ERRORS OF ESTIMATION

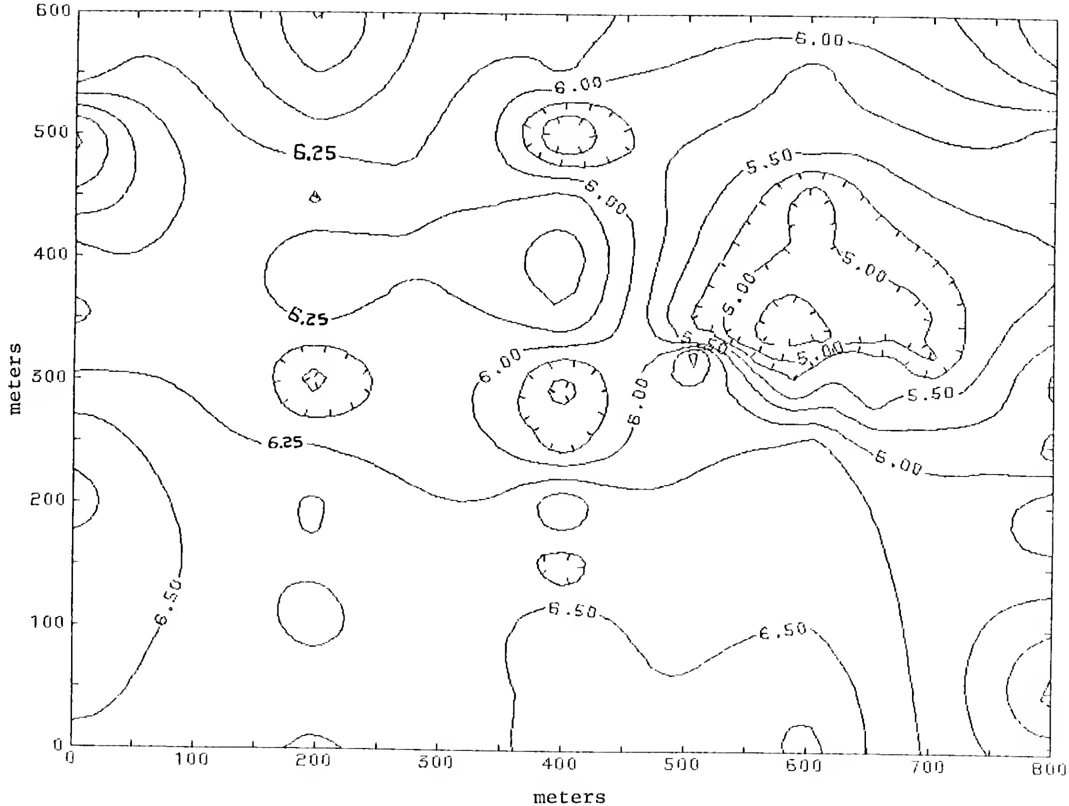


Fig. C-1. Kriged KCl-pH, large grid (increment is 0.25).

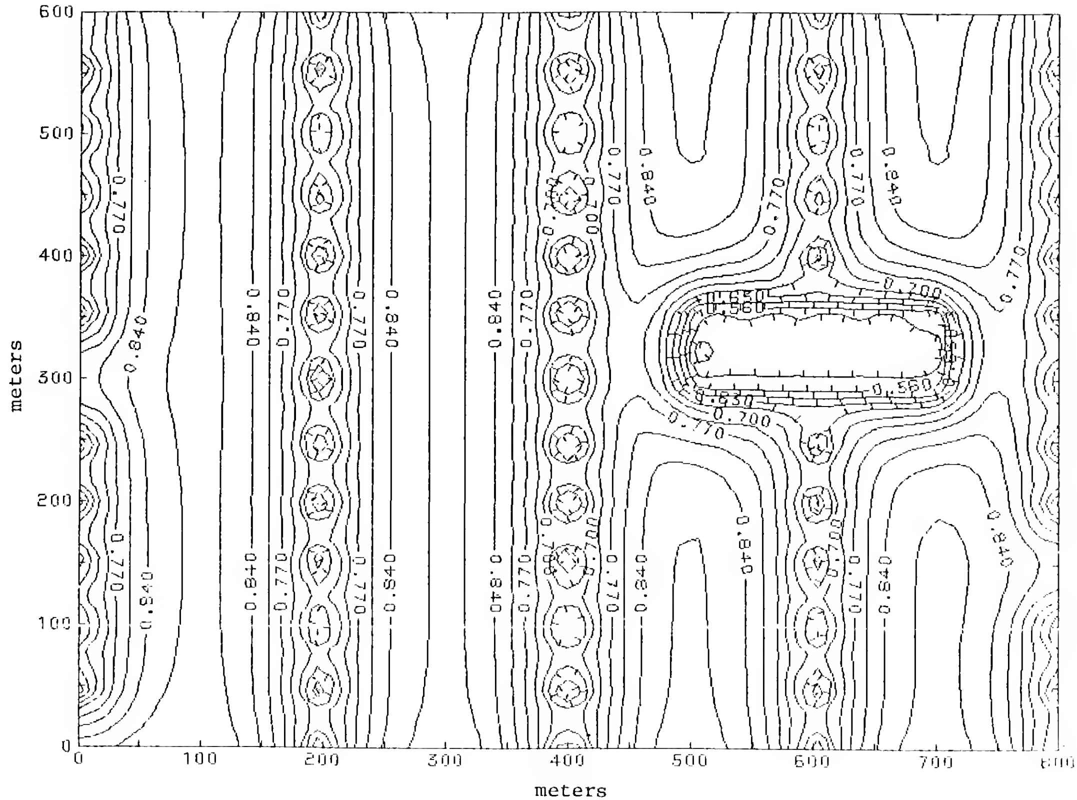


Fig. C-2. Error of Kriged KCl-pH, large grid (increment is 0.035).

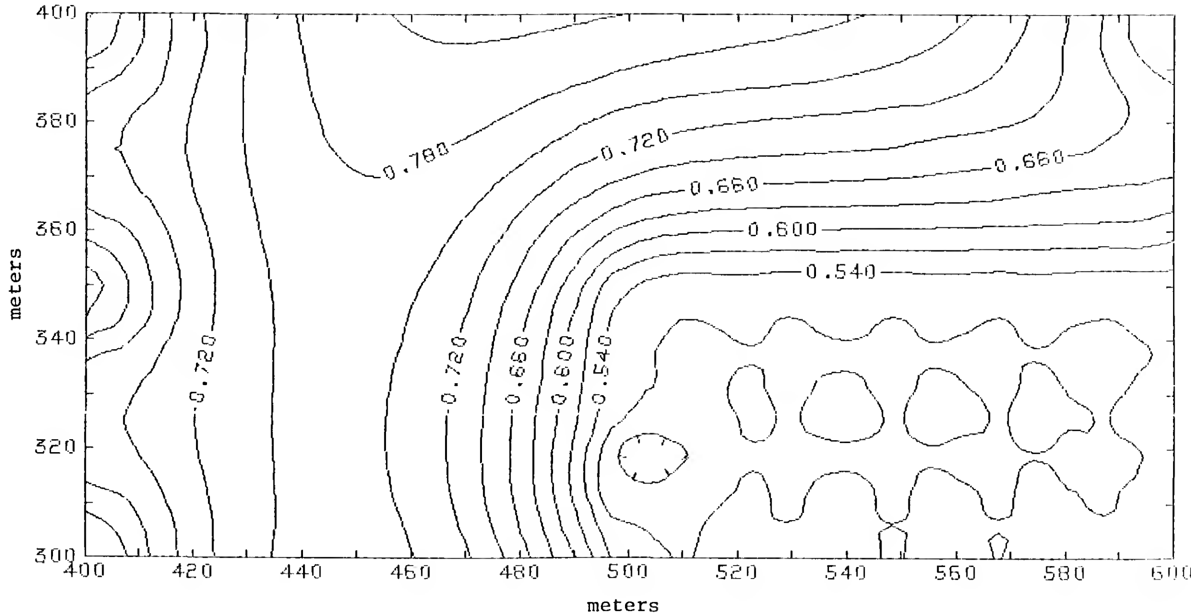


Fig. C-3. Error of Kriged KCl-pH, small map (increment is 0.03).

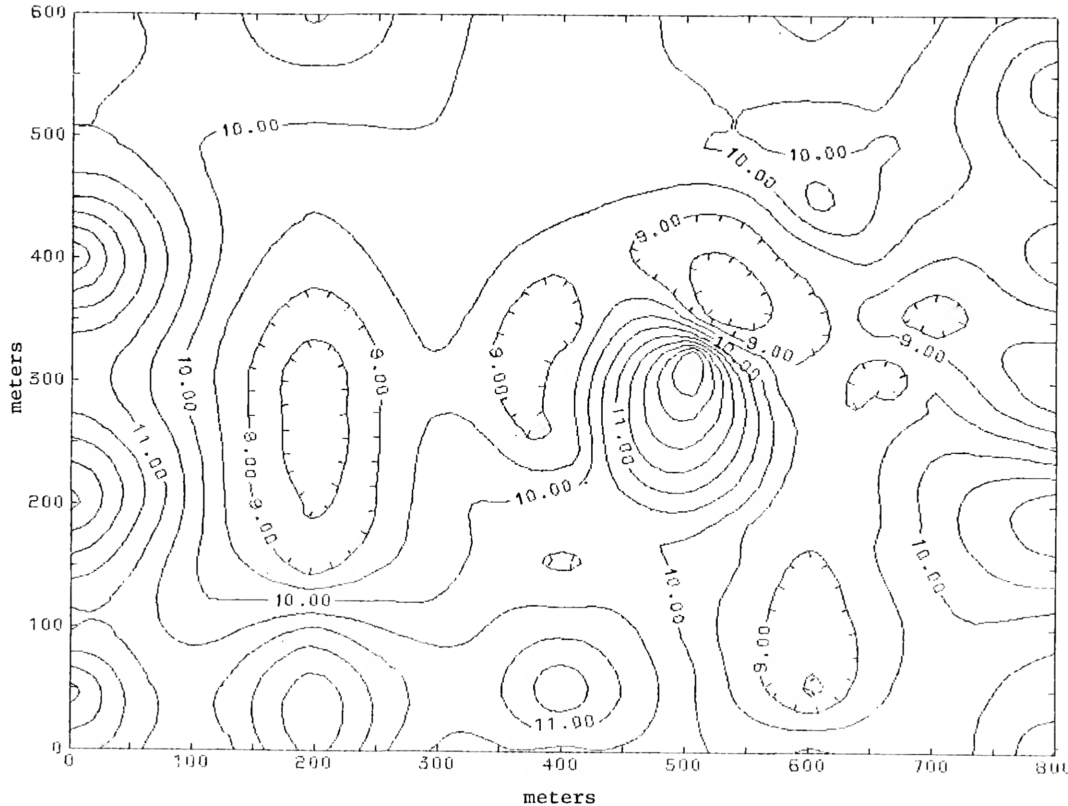


Fig. C-4. Kriged CEC, large grid (increment is 0.5 meq/100 g).

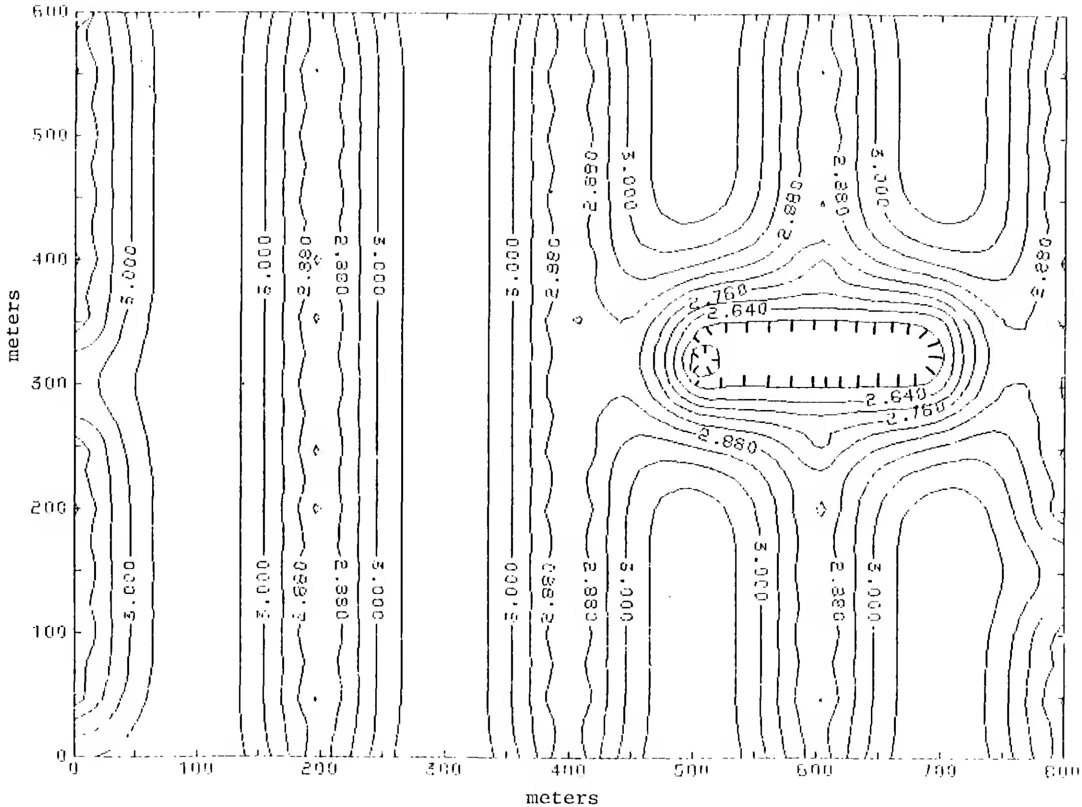


Fig. C-5. Error of Kriged CEC, large grid (increment is 0.06 meq/100 g).

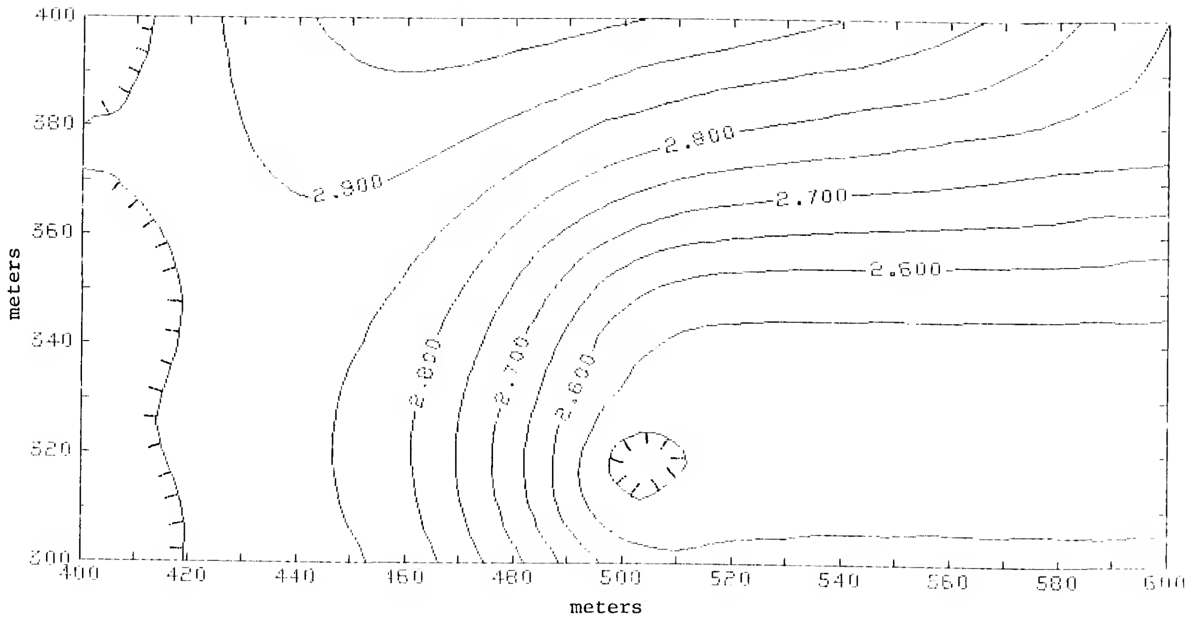


Fig. C-6. Error of Kriged CEC, small map (increment is 0.05).

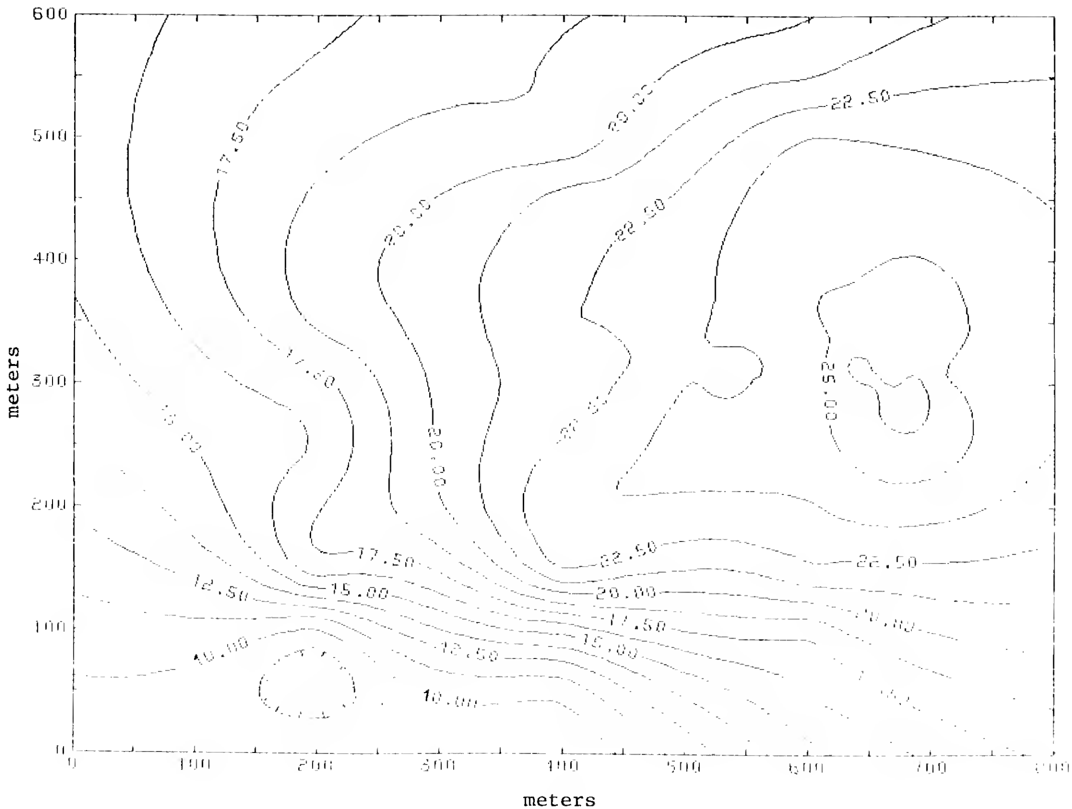


Fig. C-7. Kriged elevation, large grid (increment is 1.25 ft).

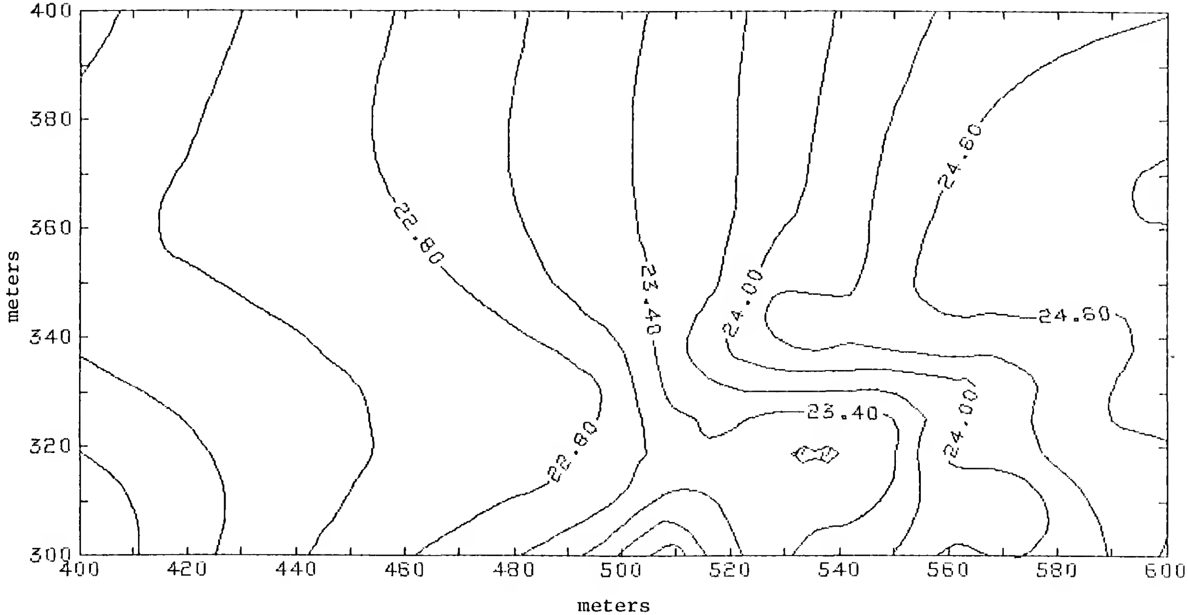


Fig. C-8. Kriged elevation, small map (increment is 0.3 ft).

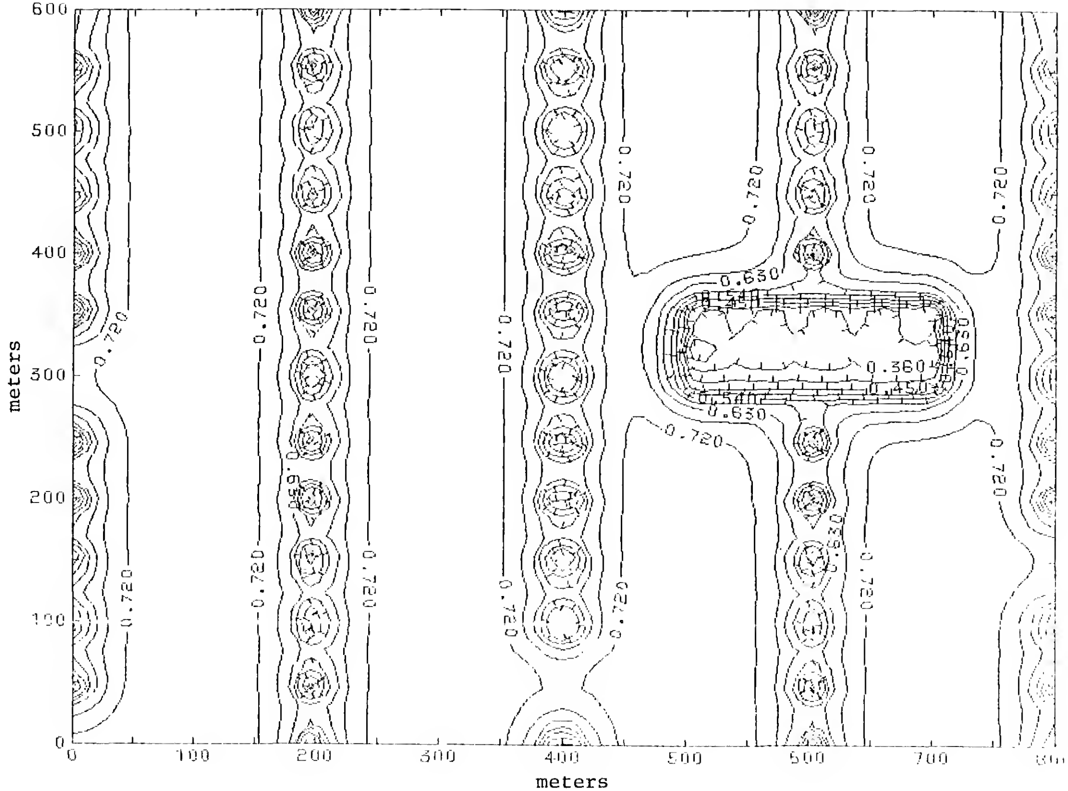


Fig. C-9. Error of Kriged H_2O-pH, large grid (increment is 0.045).

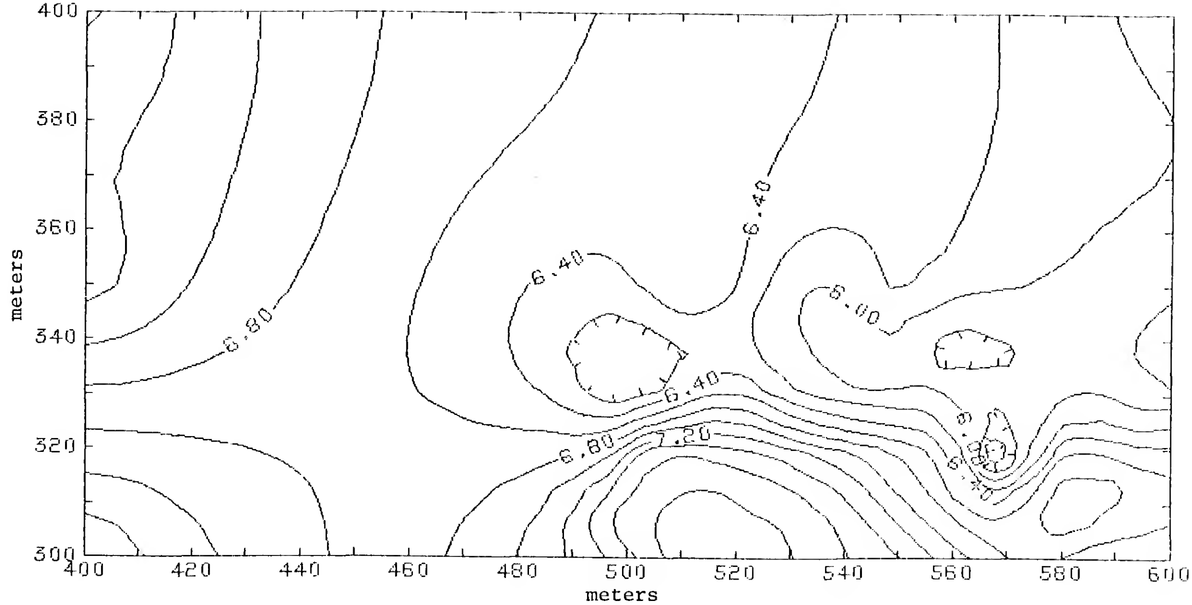


Fig. C-10. Kriged H_2O-pH, small map (increment is 0.2).

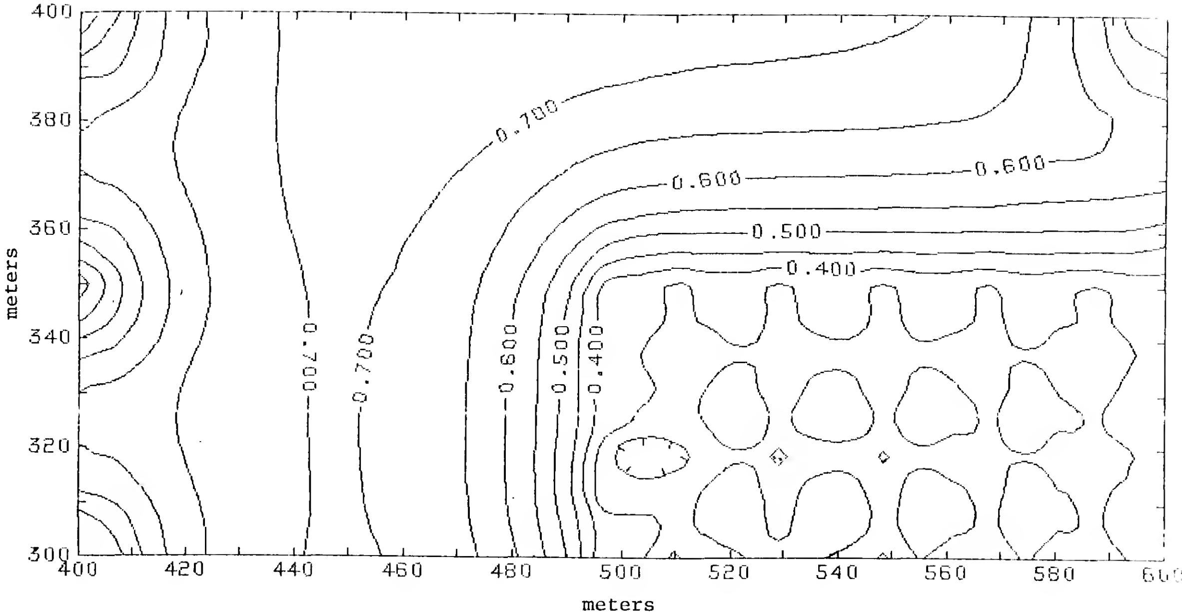


Fig. C-11. Error of Kriged H_2O-pH, small map (increment is 0.05).

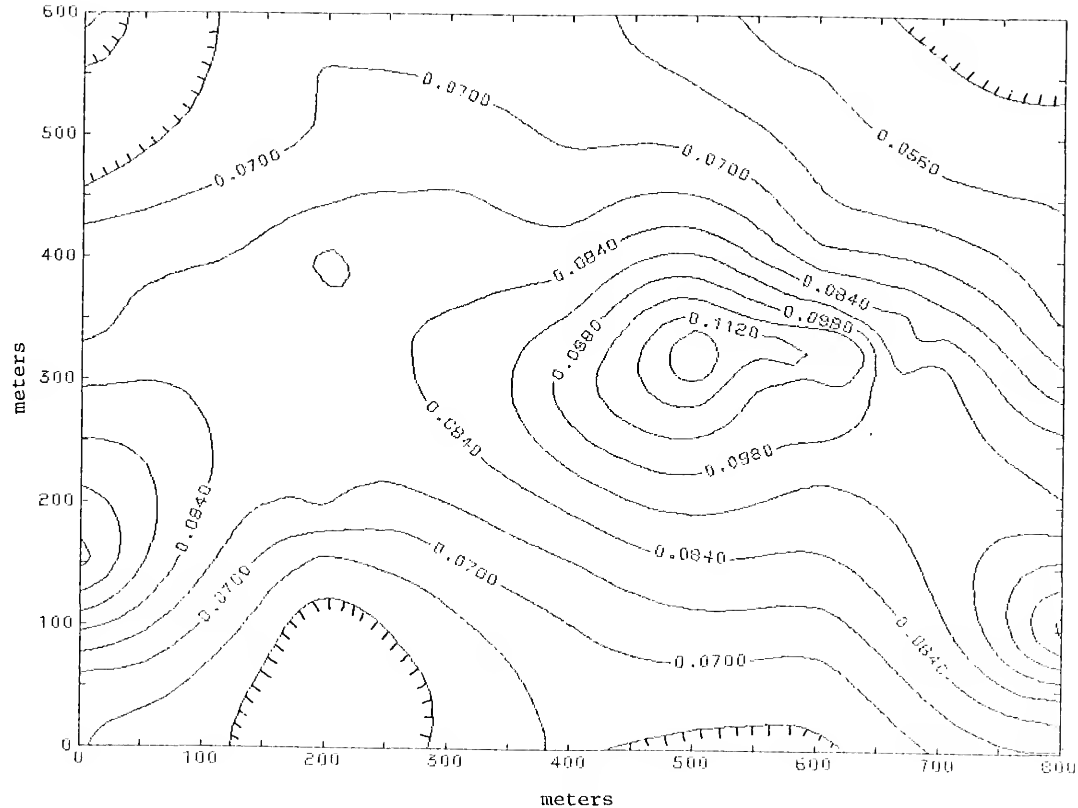


Fig. C-12. Kriged extractable K, large grid (increment is 0.007 meq/100 g).

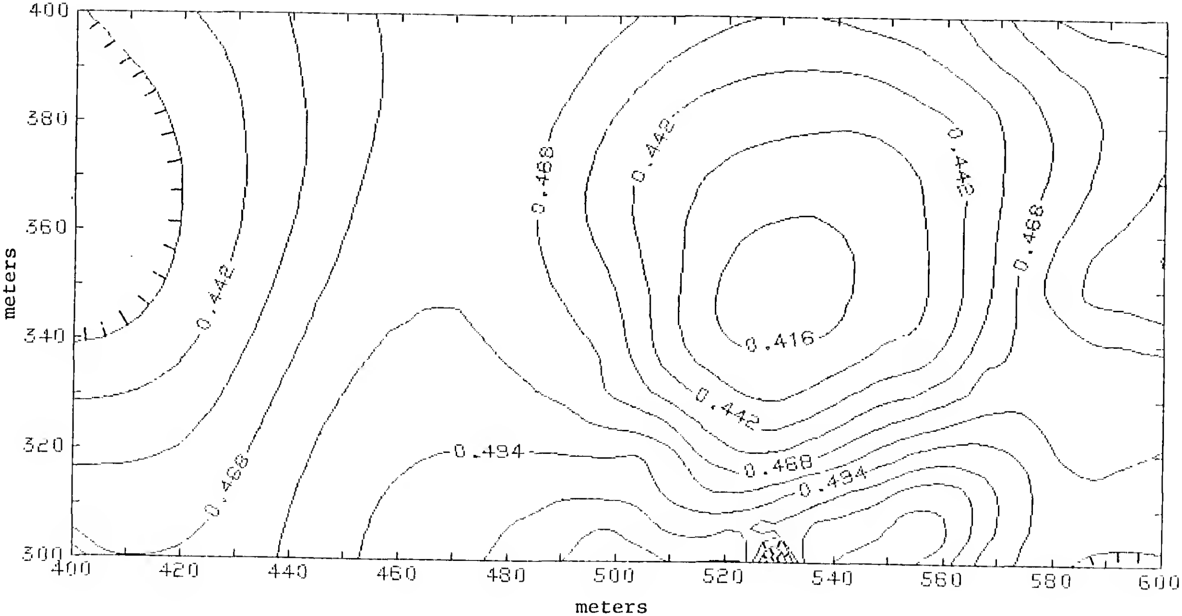


Fig. C-13. Kriged organic C, small map (increment is 0.013%).

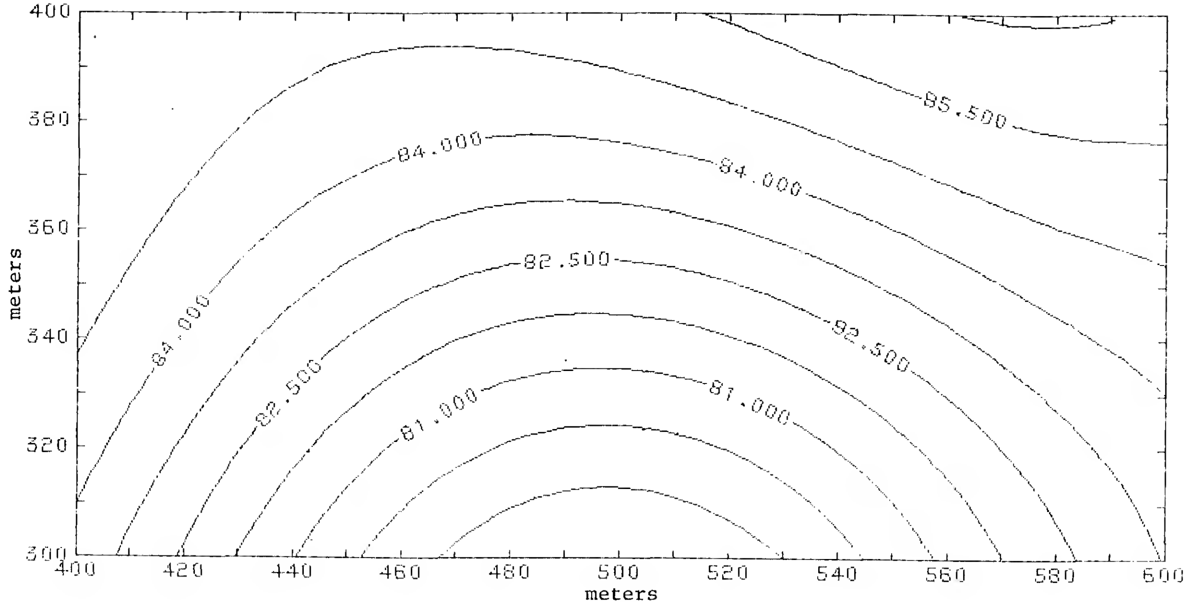


Fig. C-14. Kriged sand, small map (increment is 0.75%).

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Victor W. Carlisle

V.W. Carlisle, Chairman
Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Randall B. Brown

R.B. Brown
Assistant Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mary E. Collins

M.E. Collins
Assistant Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

D.L. Myhre

D.L. Myhre
Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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May, 1985

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